SCIENTIFIC MEMOIRS

EDITED BY

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PROFESSOR OF PHYSICS IN JOHNS HOPKINS UNIVERSITY

XII

THE DISCOVERY OF INDUCED ELECTRIC CURRENTS

Volume II

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OF

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GENERAL CONTENTS

Faraday's Original Experiments

By Dr. BENCE JONES

Sections selected from *Life and Letters of Faraday*, Vol. II, pp. 1–6.

On August 29, 1831, Faraday began his "Electrical Researches."

In December 1824, he believed with all his energy that as voltaic electricity powerfully affects a magnet, so the magnet ought to exert a reaction upon the electric current. Guided by this idea, he made an experiment, of which one part (the passage of a magnet through a metallic helix connected with a galvanometer), if separated from the rest of the experiment, would then have made the great discovery of magneto-electricity. This experiment he published in the "Quarterly Journal of Science," July 1825, p. 338.

In November 1825, also, he had failed to discover voltaic induction. He passed a current through one wire, which was lying close to another wire, which communicated with a galvanometer, and found 'no result.' The momentary existence of the phenomena of induction then escaped him.

Again, December 2, 1825, and April 22, 1828, he made experiments which gave 'no result.' These experiments were not published.

The good time was now come [*i. e., August 29, 1831*]. The first paragraph in the laboratory note-book is 'Experiments on the production of electricity from magnetism.' His first experiment, detailed in the second paragraph, records the discovery by which he will be forever known.

'I have had an iron ring made (soft iron), iron round and 7/8ths of an inch thick, and ring six inches in external diameter. Wound many coils of copper round, one half of the coils being separated by twine and calico; there were three lengths of wire, each about twenty-four feet long, and they could be connected

as one length, or used as separate lengths. By trials with a trough each was insulated from the other. Will call this side of the ring A. On the other side, but separated by an inter-

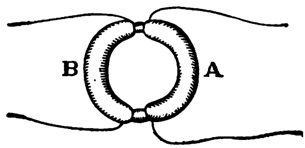

FIG. 1.

val, was wound wire in two pieces, together amounting to about sixty feet in length, the direction being as with the former coils. This side call B.

'Charged a battery of ten pairs of plates four inches square. Made the coil on B side one coil, and connected its extremities by a copper wire passing to a distance, and just over a magnetic needle (three feet from wire ring), then connected the ends of one of the pieces on A side with battery: immediately a sensible effect on needle. It oscillated and settled at last in original position. On breaking connection of A side with battery, again a disturbance of the needle.'

In the 17th paragraph, written on the 30th, he says, 'May not these transient effects be connected with causes of difference between power of metals at rest and in motion in Arago's experiments?'

After this he prepared fresh apparatus. Writing to his friend R. Phillips, September 23, he says: 'I am busy just now again on electro-magnetism, and think I have got hold of a good thing, but can't say. It may be a weed instead of a fish that, after all my labour, I may at last pull up.'

September 24 was the third day of his experiments. He began paragraph 21 by trying to find the effect of one helix of wire, carrying the voltaic current of ten pairs of plates, upon another wire connected with a galvanometer. 'No induction sensible.' Paragraph 22.

In paragraph 33 he says, 'An iron cylinder had a helix wound on it. The ends of the wires of the helix were connected with the indicating helix at a distance by copper wire. Then the iron placed between the poles of bar magnets as in accompanying figure. Every time the magnetic contact at N or S was made

or broken, there was magnetic motion at the indicating helix,—the effect being, as in former cases, not permanent, but a mere momentary push or pull. But if the electric communication (*i. e.,* by the copper wire) was broken, then the disjunction and contacts produced no effect whatever. Hence here distinct conversion of magnetism into electricity.'

The fifth day of experiment was October 17. Paragraph 57 describes the discovery of the production of electricity by the approximation of a magnet to a wire.

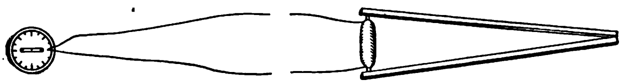

FIG. 2.

'A cylindrical bar magnet three-quarters of an inch in diameter, and eight inches and a half in length, had one end just inserted into the end of the helix cylinder (220 feet long); then it was quickly thrust in the whole length, and the *galvanometer* needle moved; then pulled out, and again the *needle moved,* but in the opposite direction. This effect was repeated every time the magnet was put in or out, and therefore a wave of electricity was so produced from *mere approximation of a magnet,* and not from its formation *in situ.*'

The ninth day of his experiments was October 28, and this day he 'made a copper disc turn around between the poles of the great horseshoe magnet of the Royal Society. The axis and edge of the disc were connected with a galvanometer. The needle moved as the disc turned.' The next day he made experiments, November 4, he found 'that a copper wire one eighth of an inch drawn between the poles and conductors produced the effect.'

In ten days of experiment these splendid results were obtained. He collected the facts into the first series of 'Experimental Researches in Electricity.' It was read, November 24th, at the Royal Society.

EXPERIMENTAL RESEARCHES IN ELECTRICITY

By MICHAEL FARADAY

Papers on Electro-Magnetic Induction

FIRST SERIES

CONTENTS

FIRST SERIES

§ 1. On the Induction of Electric Currents. § 2. On the Evolution of Electricity from Magnetism. § 3. On a New Electrical Condition of Matter. § 4. On Arago's Magnetic Phenomena

Read November 24, 1831

1. The power which electricity of tension possesses of causing an opposite electrical state in its vicinity has been expressed by the general term Induction; which, as it has been received into scientific language, may also, with propriety, be used in the same general sense to express the power which electrical currents may possess of inducing any particular state upon matter in their immediate neighborhood, otherwise indifferent. It is with this meaning that I purpose using it in the present paper.

2. Certain effects of the induction of electrical currents have already been recognized and described: as those of magnetization; Ampère's experiments of bringing a copper disc near to a flat spiral; his repetition with electro-magnets of Arago's extraordinary experiments, and perhaps a few others. Still it appeared unlikely that these could be all the effects which induction by currents could produce; especially, as, upon dispensing with iron, almost the whole of them disappear, whilst yet an infinity of bodies, exhibiting definite phenomena of induction with electricity of tension still remain to be acted upon by the induction of electricity in motion.

3. Further: whether Ampère's beautiful theory were adopted, or any other, or whatever reservation were mentally made, still it appeared very extraordinary, that as every electric current was accompanied by a corresponding intensity of magnetic action at right angles to the current, good conductors of electricity, when placed within the sphere of this action, should not have any

current induced through them, or some sensible effect produced equivalent in force to such a current.

4. These considerations, with their consequence, the hope of obtaining electricity from ordinary magnetism, have stimulated me at various times to investigate experimentally the inductive effect of electric currents. I lately arrived at positive results; and not only had my hopes fulfilled, but obtained a key which appeared to me to open out a full explanation of Arago's magnetic phenomena, and also to discover a new state, which may probably have great influence in some of the most important effects of electric currents.

5. These results I purpose describing, not as they were obtained, but in such a manner as to give the most concise view of the whole.

§ 1. *Induction of Electric Currents*

6. About twenty-six feet of copper wire one twentieth of an inch in diameter were wound round a cylinder of wood as a helix, the different spires of which were prevented from touching by a thin interposed twine. This helix was covered with calico, and then a second wire applied in the same manner. In this way twelve helices were superposed, each containing an average length of wire of twenty-seven feet, and all in the same direction. The first, third, fifth, seventh, ninth, and eleventh of these helices were connected at their extremities end to end, so as to form one helix; the others were connected in a similar manner; and thus two principal helices were produced, closely interposed, having the same direction, not touching anywhere, and each containing one hundred and fifty-five feet in length of wire.

7. One of these helices was connected with a galvanometer, the other with a voltaic battery of ten pairs of plates four inches square, with double coppers and well charged; yet not the slightest sensible deflection of the galvanometer needle could be observed.

8. A similar compound helix, consisting of six lengths of copper and six of soft iron wire, was constructed. The resulting iron helix contained two hundred and fourteen feet of wire, the resulting copper helix two hundred and eight feet; but whether the current from the trough was passed through the cop-

per or the iron helix, no effect upon the other could be perceived at the galvanometer.

9. In these and many similar experiments no difference in action of any kind appeared between iron and other metals.

10. Two hundred and three feet of copper wire in one length were coiled round a large block of wood; other two hundred and three feet of similar wire were interposed as a spiral between the turns of the first coil, and metallic contact everywhere prevented by twine. One of these helices was connected with a galvanometer, and the other with a battery of one hundred pairs of plates four inches square, with double coppers, and well charged. When the contact was made, there was a sudden and very slight effect at the galvanometer, and there was also a similar slight effect when the contact with the battery was broken. But whilst the voltaic current was continuing to pass through the one helix, no galvanometrical appearances nor any effect like induction upon the other helix could be perceived, although the active power of the battery was proved to be great, by its heating the whole of its own helix, and by the brilliancy of the discharge when made through charcoal.

11. Repetition of the experiments with a battery of one hundred and twenty pairs of plates produced no other effects; but it was ascertained, both at this and the former time, that the slight deflection of the needle occurring at the moment of completing the connection, was always in one direction, and that the equally slight deflection produced when the contact was broken, was in the other direction; and also, that these effects occurred when the first helices were used (6, 8).

12. The results which I had by this time obtained with magnets led me to believe that the battery current through one wire, did, in reality, induce a similar current through the other wire, but that it continued for an instant only, and partook more of the nature of the electrical wave passed through from the shock of a common Leyden jar than of the current from a voltaic battery, and therefore might magnetize a steel needle, although it scarcely affected the galvanometer.

13. This expectation was confirmed; for on substituting a small hollow helix, formed round a glass tube, for the galvanometer, introducing a steel needle, making contact as before between the battery and the inducing wire (7, 10), and then removing

the needle before the battery contact was broken, it was found magnetized.

14. When the battery contact was first made, then an unmagnetized needle introduced into the small indicating helix (13), and lastly the battery contact broken, the needle was found magnetized to an equal degree apparently as before; but the poles were of the contrary kind.

15. The same effect took place on using the large compound helices first described (6, 8).

16. When the unmagnetized needle was put into the indicating helix, before contact of the inducing wire with the battery, and remained there until the contact was broken, it exhibited little or no magnetism; the first effect having been nearly neutralized by the second (13, 14). The force of the induced current upon making contact was found always to exceed that of the induced current at breaking of contact and if therefore the contact was made and broken many times in succession, whilst the needle remained in the indicating helix, it at last came out not unmagnetized, but a needle magnetized as if the induced current upon making contact had acted alone on it. This effect may be due to the accumulation (as it is called) at the poles of the unconnected pile, rendering the current upon first making contact more powerful than what it is afterwards, at the moment of breaking contact.

17. If the circuit between the helix or wire under induction and the galvanometer or indicating spiral was not rendered complete *before* the connection between the battery and the inducing wire was completed or broken, then no effects were perceived at the galvanometer. Thus, if the battery communications were first made, and then the wire under induction connected with the indicating helix, no magnetizing power was there exhibited. But still retaining the latter communications, when those with the battery were broken, a magnet was formed in the helix, but of the second kind (14) *i. e.,* with poles indicating a current in the same direction to that belonging to the battery current, or to that always induced by that current at its cessation.

18. In the preceding experiments the wires were placed near to each other and the contact with the inducing one with the battery made when the inductive effect was required; but as the

particular action might be supposed to be exerted only at the moments of making and breaking contact, the induction was produced in another way. Several feet of copper wire were stretched in wide zigzag forms, representing the letter W, on one surface of a broad board; a second wire was stretched in precisely similar forms on a second board, so that when brought near the first, the wires should everywhere touch except that a sheet of thick paper was interposed. One of these wires was connected with the galvanometer and the other with a voltaic battery. The first wire was then moved towards the second and as it approached, the needle was deflected. Being then removed the needle was deflected in the opposite direction. By first making the wires approach and then recede simultaneously with the vibrations of the needle the latter soon became very extensive; but when the wires ceased to move from or towards each other, the galvanometer-needle soon came to its usual position.

19. As the wires approximated, the induced current was in the *contrary* direction to the inducing current. As the wires receded the induced current was in the *same* direction as the inducing current. When the wires remained stationary there was no induced current (54).

20. When a small voltaic arrangement was introduced into the circuit between the galvanometer (10) and its helix or wire, so as to cause a permanent deflection of 30° or 40°, and then the battery of 100 pairs of plates connected with the inducing wire, there was an instantaneous action as before (11); but the galvanometer-needle immediately resumed and retained its place unaltered, notwithstanding the continued contact of the inducing wire with the trough: such was the case in whichever way the contacts were made (33).

21. Hence it would appear that collateral currents, either in the same or in opposite directions exert no permanent inducing power on each other, affecting their quantity or tension.

22. I could obtain no evidence by the tongue, by spark, or by heating fine wire or charcoal, of the electricity passing through the wire under induction; neither could I obtain any chemical effects, though the contacts with metallic and other solutions were made and broken alternately with those of the battery, so that the second effect of induction should not oppose or neutralize the first (13, 16).

23. This deficiency of effect is not because the induced current of electricity cannot pass fluids, but probably because of its brief duration and feeble intensity; for on introducing two large copper plates into the circuit on the induced side (20), the plates being immersed in brine, but prevented from touching each other by an interposed cloth, the effect at the indicating galvanometer or helix occurred as before. The induced electricity could also pass through a voltaic trough (20). When, however, the quantity of interposed fluid was reduced to a drop, the galvanometer gave no indication.

24. Attempts to obtain similar effects by the use of wires conveying ordinary electricity were doubtful in the results. A compound helix, similar to that already described, containing eight elementary helices (6), was used. Four of the helices had their similar ends bound together by wire, and the two general terminations thus produced connected with the small magnetizing helix containing an unmagnetized needle (13). The other four helices were similarly arranged, but their ends connected with a Leyden jar. On passing the discharge, the needle was found to be a magnet; but it appeared probable that a part of the electricity of the jar had passed off to the small helix, and so magnetized the needle. There was indeed no reason to expect that the electricity of a jar possessing as it does great tension, would not diffuse itself through all the metallic matter interposed between the coatings.

25. Still it does not follow that the discharge of ordinary electricity through a wire does not produce analogous phenomena to those arising from voltaic electricity; but as it appears impossible to separate the effects produced at the moment when the discharge begins to pass, from the equal and contrary effects produced when it ceases to pass (16), inasmuch as with ordinary electricity these periods are simultaneous, so there can be scarcely any hope that in this form of experiment they can be perceived.

26. Hence it is evident that the currents of voltaic electricity present phenomena of induction somewhat analogous to those produced by electricity of tension, although, as will be seen hereafter, many differences exist between them. The result is the production of other currents (but which are only momentary), parallel, or tending to parallelism, with the inducing current. By reference to the poles of the needle formed in the

indicating helix (13, 14), and to the deflections of the galvanometer needle (11), it was found in all cases that the induced current, produced by the first action of the inducing current, was in the contrary direction to the latter, but that the current produced by the cessation of the inducing current was in the same direction (19). For the purpose of avoiding periphrasis, I propose to call this action of the current from the voltaic battery *volta-electric induction.* The properties of the second wire, after induction has developed the first current, and whilst the electricity from the battery continues to flow through its inducing neighbor (10, 18), constitute a peculiar electric condition, the consideration of which will be resumed hereafter (60). All these results have been obtained with a voltaic apparatus consisting of a single pair of plates.

§ 2. *Evolution of Electricity from Magnetism*

27. A welded ring was made of soft round bar-iron, the metal being seven eighths of an inch in thickness, and the ring six inches in external diameter. Three helices were put round one part of this ring, each containing about twenty-four feet of copper wire one twentieth of an inch thick; they were insulated from the iron and each other, and superposed in the manner before described (6), occupying about nine inches in length upon the ring. They could be used separately or conjointly; the group may be distinguished by the letter A, Fig. 1. On the other part of the ring about sixty feet of similar copper wire in two pieces were applied in the same manner, forming a helix B, which had the same common direction with the helices of A, but being separated from it at each extremity by about half an inch of the uncovered iron.

28. The helix B, was connected by copper wires with a galvanometer three feet from the ring. The helices of A were connected end to end so as to form one common helix, the extremities of which were connected with a battery of ten pairs of plates four inches square. The galvanometer was immediately affected, and to a degree far beyond what has been described when with a battery of tenfold power helices *without iron* were used (10); but though the contact was continued, the

effect was not permanent, for the needle soon came to rest in its natural position, as if quite indifferent to the attached electro-magnetic arrangement. Upon breaking the contact with the battery, the needle was again powerfully deflected, but in the contrary direction to that induced in the first instance.

29. Upon arranging the apparatus so that B should be out of use, the galvanometer be connected with one of the three wires of A (27), and the other two made into a helix through which the current from the trough (28) was passed, similar but rather more powerful effects were produced.

30. When the battery contact was made in one direction, the galvanometer-needle was deflected on the one side; if made in the other direction, the deflection was on the other side. The deflection on breaking the battery contact was always the reverse of that produced by completing it. The deflection on making a battery contact always indicated an induced current in the opposite direction to that from the battery; but on breaking the contact the deflection indicated an induced current in the same direction as that of the battery. No making or breaking of the contact at B side, or in any part of the galvanometer circuit, produced any effect at the galvanometer. No continuance of the battery current caused any deflection of the galvanometer-needle. As the above results are common to all these experiments, and to similar ones with ordinary magnets to be hereafter detailed, they need not be again particularly described.

31. Upon using the power of 100 pairs of plates (10) with this ring, the impulse at the galvanometer, when contact was completed or broken, was so great as to make the needle spin round rapidly four or five times, before the air and terrestrial magnetism could reduce its motion to mere oscillation.

32. By using charcoal at the ends of the B helix, a minute *spark* could be perceived when the contact of the battery with A was completed. This spark could not be due to any diversion of a part of the current of the battery through the iron to the helix B; for when the battery contact was continued, the galvanometer still resumed its perfectly indifferent state (28). The spark was rarely seen on breaking contact. A small platina wire could not be ignited by this induced current; but there seems every reason to believe that the effect would be obtained

by using a stronger original current or a more powerful arrangement of helices.

33. A feeble voltaic current was sent through the helix B and the galvanometer, so as to deflect the needle of the latter 30° or 40°, and then the battery of one hundred pairs of plates connected with A; but after the first effect was over, the galvanometer-needle resumed exactly the position due to the feeble current transmitted by its own wire. This took place in whichever way the battery contacts were made, and shows that here again (20) no permanent influence of the currents upon each other, as to their quantity and tension exists.

34. Another arrangement was then employed connecting the former experiments on volta-electric induction (6-26) with the present. A combination of helices like that already described (6) was constructed upon a hollow cylinder of pasteboard: there were eight lengths of copper wire, containing altogether 220 feet; four of these helices were connected end to end, and then with the galvanometer (7); the other intervening four were also connected end to end, and the battery of one hundred pairs discharged through them. In this form the effect on the galvanometer was hardly sensible (11), though magnets could be made by the induced current (13). But when a soft iron cylinder seven eighths of an inch thick, and twelve inches long, was introduced into the pasteboard tube, surrounded by the helices, then the induced current affected the galvanometer powerfully, and with all the phenomena just described (30). It possessed also the power of making magnets with more energy, apparently, than when no iron cylinder was present.

35. When the iron cylinder was replaced by an equal cylinder of copper, no effect beyond that of the helices alone was produced. The iron cylinder arrangement was not so powerful as the ring arrangement already described (27).

36. Similar effects were then produced by *ordinary magnets:* thus the hollow helix just described (34) had all its elementary helices connected with the galvanometer by two copper wires, each five feet in length; the soft iron cylinder was introduced into its axis; a couple of bar-magnets each twenty-four inches long, were arranged with their opposite poles at one end in contact, so as to resemble a horse-shoe magnet, and then contact

made between the other poles and the ends of the iron cylinder, so as to convert it for the time into a magnet, Fig. 2, by breaking the magnetic contacts or reversing them, the magnetism of the iron cylinder could be destroyed or reversed at pleasure.

37. Upon making magnetic contact, the needle was deflected; continuing the contact, the needle became indifferent, and resumed its first position; on breaking the contact it was again deflected, but in the opposite direction to the first effect, and then it again became indifferent. When the magnetic contacts were reversed the deflections were reversed.

38. When the magnetic contact was made, the deflection was such as to indicate an induced current of electricity in the opposite direction to that fitted to form a magnet, having the same polarity as that really produced by contact with the bar magnets. Thus when the marked and unmarked poles were placed as in Fig. 3, the current in the helix was in the direction represented, P being supposed to be the end of the wire going to the positive pole of the battery, or that end towards which the zinc plates face, and N the negative wire. Such a current would have converted the cylinder into a magnet of the opposite kind to that formed by contact with the poles A and B; and such a current moves in the opposite direction to the currents which in M. Ampère's beautiful theory are considered as constituting a magnet in the position figured.*

39. But as might be supposed that in all the preceding

* The relative position of an electric current and a magnet is by most persons found very difficult to remember, and three or four helps to the memory have been devised by M. Ampère and others. I venture to suggest the following as a very simple and effectual assistance in these and similar latitudes. Let the experimenter think he is looking down upon a dipping needle, or upon the pole of the earth, and then let him think upon the direction of the motion of the hands of a watch, or of a screw moving direct; currents in that direction around a needle would make it into such a magnet as the dipping needle, or would themselves constitute an electro-magnet of similar qualities; or if brought near a magnet would tend to make it take that direction; or would themselves be moved into that position by a magnet so placed; or in M. Ampère's theory are considered as moving in that direction in the magnet. These two points of the position of the dipping needle and the motion of the watch hands being remembered, any other relation of the current and the magnet can be at once deduced from it.

experiments of this section, it was by some peculiar effect taking place during the formation of the magnet, and not by its mere virtual approximation, that the momentary induced current was excited, the following experiment was made. All the similar ends of the compound hollow helix (34) were bound together by copper wire, forming two general terminations, and these were connected with the galvanometer. The soft iron cylinder

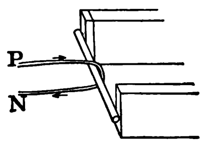

FIG. 3.

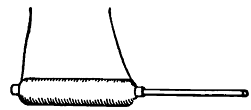

FIG. 4.

(34) was removed, and a cylindrical magnet three-quarters of an inch in diameter and eight inches and a half in length, used instead. One end of this magnet was introduced into the axis of the helix, Fig. 4, and then, the galvanometer-needle being stationary, the magnet was suddenly thrust in; immediately the needle was deflected in the same direction as if the magnet had been formed by either of the two preceding processes (34, 36). Being left in, the needle resumed its first position, and then the magnet being withdrawn the needle was deflected in the opposite direction. These effects were not great; but by introducing and withdrawing the magnet, so that the impulse each time should be added to those previously communicated to the needle, the latter could be made to vibrate through an arc of 180° or more.

40. In this experiment the magnet must not be passed entirely through the helix, for then a second action occurs. When the magnet is introduced the needle at the galvanometer is deflected in a certain direction; but being in, whether it be pushed quite through or withdrawn, the needle is deflected in a direction the reverse of that previously produced. When the magnet is passed in and through at one continuous motion, the needle moves one way, is then suddenly stopped, and finally moves the other way.

41. If such a hollow helix as that described (34) be laid east and west (or in any other constant position), and a magnet

be retained east and west, its marked pole always being one way; then whichever end of the helix the magnet goes in at, and consequently whichever pole of the magnet enters first, still the needle is deflected the same way: on the other hand whichever direction is followed in withdrawing the magnet, the deflection is constant, but contrary to that due to its entrance.

42. These effects are simple consequences of the *law* hereafter to be described (114).

43. When the eight elementary helices were made one long helix, the effect was not so great as in the arrangement described. When only one of the eight helices was used, the effect was also much diminished. All care was taken to guard against any direct action of the inducing magnet upon the galvanometer, and it was found that by moving the magnet in the same direction, and to the same degree on the outside of the helix no effect on the needle was produced.

44. The Royal Society are in possession of a large compound magnet formerly belonging to Dr. Gowin Knight, which, by permission of the President and Council, I was allowed to use in the prosecution of these experiments: it is at present in the charge of Mr. Christie, at his house at Woolwich, where, by Mr. Christie's kindness, I was at liberty to work; and I have to acknowledge my obligations to him for his assistance in all the experiments and observations made with it. This magnet is composed of about 450 bar magnets, each fifteen inches long, one inch wide, and half an inch thick, arranged in a box so as to present at one of its extremities two external poles, Fig. 5. These poles projected horizontally six inches from the box, were each twelve inches high and three inches wide. They were nine inches apart; and when a soft iron cylinder, three-quarters of an inch in diameter and twelve inches long, was put across from one to the other, it required a force of nearly one hundred pounds to break the contact. The pole to the left in the figure is the marked pole.*

* To avoid any confusion as to the poles of the magnet, I shall designate the pole pointing to the north as the marked pole; I may occasionally speak of the north and south ends of the needle, but do not mean thereby north and south poles. That is by many considered the true north pole of a needle which points to the south; but in this country it is often called the south pole.

45. The indicating galvanometer, in all experiments made with this magnet, was about eight feet from it, not directly in front of the poles, but about 16° or 17° on one side. It was found that on making or breaking the connection of the poles by soft iron, the instrument was slightly affected; but all error of observation arising from this cause was easily and carefully avoided.

46. The electrical effects exhibited by this magnet were very striking. When a soft iron cylinder thirteen inches long was put through the compound hollow helix, with its ends arranged

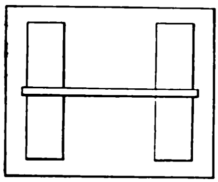

FIG. 5.

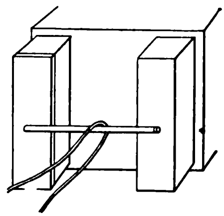

FIG. 6.

as two general terminations (39), these connected with the galvanometer, and the iron cylinder brought in contact with the two poles of the magnet, Fig. 5, so powerful a rush of electricity took place that the needle whirled round many times in succession.*

47. Notwithstanding this great power, if the contact were continued, the needle resumed its natural position, being entirely uninfluenced by the position of the helix (30). But on breaking the magnetic contact, the needle was whirled round in the opposite direction with a force equal to the former.

48. A piece of copper plate wrapped *once* round the iron cylinder like a socket, but with interposed paper to prevent contact, had its edges connected with the wires of the galvanometer. When the iron was brought in contact with the poles the galvanometer was strongly affected.

49. Dismissing the helices and sockets, the galvanometer wire

* A soft iron bar in the form of a lifter to a horseshoe magnet, when supplied with a coil of this kind round the middle of it, becomes, by juxtaposition with a magnet, a ready source of a brief but determinate current of electricity.

was passed over, and consequently only half round the iron cylinder, Fig. 6, but even then a strong effect upon the needle was exhibited, when the magnetic contact was made or broken.

50. As the helix with its iron cylinder was brought towards the magnetic poles, but *without making contact,* still powerful effects were produced. When the helix, without the iron cylinder, and consequently containing no metal but copper, was approached to, or placed between the poles (44), the needle was thrown 80° or 90°, or more, from its natural position. The inductive force was, of course, greater, the nearer the helix, either with or without its iron cylinder, was brought to the poles; but otherwise the same effects were produced, whether the helix, etc., was or was not brought into contact with the magnet; *i. e.,* no permanent effect on the galvanometer was produced; and the effects of approximation and removal were the reverse of each other (30).

51. When a bolt of copper corresponding to the iron cylinder was introduced, no greater effect was produced by the helix than without it. But when a thick iron wire was substituted, the magneto-electric induction was rendered sensibly greater.

52. The direction of the electric current produced in all these experiments with the helix, was the same as that already described (38) as obtained with the weaker bar magnets.

53. A spiral containing fourteen feet of copper wire, being connected with the galvanometer, and approximated directly towards the marked pole in the line of its axis, affected the instrument strongly; the current induced in it was in the reverse direction to the current theoretically considered by M. Ampère as existing in the magnet (38), or as the current in the electromagnet of similar polarity. As the spiral was withdrawn, the induced current was reversed.

54. A similar spiral had the current of eighty pairs of 4-inch plates sent through it so as to form an electro-magnet, and then the other spiral connected with the galvanometer (53) approximated to it; the needle vibrated, indicating a current in the galvanometer spiral the reverse of that in the battery spiral (18, 26). On withdrawing the latter spiral the needle passed in the opposite direction.

55. Single wires, approximated in certain directions towards the magnetic pole, had currents induced in them. On their

removal the currents were inverted. In such experiments the wires should not be moved in directions different to those in which they were approximated; for then occasionally complicated and irregular effects are produced, the causes of which will be very evident in the fourth part of this paper.

56. All attempts to obtain chemical effects by the induced current of electricity failed, though the precautions before described (22), and all others that could be thought of were employed. Neither was any sensation on the tongue, or any convulsive effect on the limbs of a frog, produced. Nor could charcoal or fine wire be ignited (133). But upon repeating the experiments more at leisure at the Royal Institution, with an armed loadstone belonging to Professor Daniell and capable of lifting about thirty pounds, a frog was very *powerfully convulsed* each time a magnetic contact was made. At first the convulsions could not be obtained on breaking magnetic contact; but conceiving that the deficiency of effect was because of the comparative slowness of separation, the latter act was effected by a blow, and then the frog was convulsed strongly. The more instantaneous the union or disunion is effected, the more powerful the convulsion. I thought also I could perceive the *sensation* upon the tongue and the *flash* before the eyes; but I could obtain no evidence of chemical decomposition.

57. The various experiments of this section prove, I think, most completely the production of electricity from ordinary magnetism. That its intensity should be very feeble and quantity small, cannot be considered wonderful, when it is remembered that like thermo-electricity it is evolved entirely within the substance of metals retaining all their conducting power. But an agent which is conducted along the metallic wires in the manner described; which, whilst so passing possesses the peculiar magnetic actions and force of a current of electricity; which can agitate and convulse the limbs of a frog; and which, finally, can produce a spark* by its discharge through charcoal (32), can only be electricity. As all the effects can be produced by

* For a mode of obtaining the spark from the common magnet which I have found effectual, see the *Philosophical Magazine* for June 1832, p. 5. In the same journal for November 1834, Vol. V, p. 349, will be found a method of obtaining the magneto-electric spark, still simpler in its principle, the use of soft iron being dispensed with altogether. — *Dec.* 1838.

ferruginous electro-magnets (34), there is no doubt that arrangements like the magnets of Professors Moll, Henry, Ten Eyke, and others, in which as many as two thousand pounds have been lifted, may be used for these experiments; in which case not only a brighter spark may be obtained, but wires also ignited, and, as the current can pass liquids (23), chemical action be produced. These effects are still more likely to be obtained when the magneto-electric arrangements to be explained in the fourth section are excited by the powers of such apparatus.

58. The similarity of action, almost amounting to identity, between common magnets and either electro-magnets or volta-electric currents, is strikingly in accordance with and confirmatory of M. Ampère's theory, and furnishes powerful reasons for believing that the action is the same in both cases; but, as a distinction in language is still necessary, I propose to call the agency thus exerted by ordinary magnets, *magneto-electric* or *magnelectric* induction (26).

59. The only difference which powerfully strikes the attention as existing between volta-electric and magneto-electric induction, is the suddenness of the former, and the sensible time required by the latter: but even in this early state of investigation there are circumstances which seem to indicate, that upon further inquiry this difference will, as a philosophical distinction, disappear* (68).

§3. *New Electrical State or Condition of Matter*†

60. Whilst the wire is subject either to volta-electric or magneto-electric induction, it appears to be in a peculiar state; for it resists the formation of an electrical current in it, whereas if

* For important additional phenomena and developments of the induction of electrical currents, see now the ninth series, 1048–1118. —*Dec.* 1838.

† This section having been read at the Royal Society and reported upon, and having also in consequence of a letter from myself to M. Hachette, been noticed at the French Institute, I feel bound to let it stand as part of the paper; but later investigations (intimated 73, 76, 77) of the laws governing these phenomena, induce me to think that the latter can be fully explained without admitting the electro-tonic state. My views on this point will appear in the second series of these researches.—M. F.

in its common condition, such a current would be produced; and when left uninfluenced it has the power of originating a current, a power which the wire does not possess under common circumstances. This electrical condition of matter has not hitherto been recognized, but it probably exerts a very important influence in many if not most of the phenomena produced by currents of electricity. For reasons which will immediately appear (71), I have, after advising with several learned friends, ventured to designate it as the *electro-tonic* state.

61. This peculiar condition shows no known electrical effects whilst it continues; nor have I yet been able to discover any peculiar powers exerted, or properties possessed, by matter whilst retained in this state.

62. It shows no reaction by attractive or repulsive powers. The various experiments which have been made with powerful magnets upon such metals as copper, silver, and generally those substances not magnetic, prove this point; for the substances experimented upon, if electrical conductors, must have acquired this state; and yet no evidence of attractive or repulsive powers has been observed. I have placed copper and silver discs, very delicately suspended on torsion balances *in vacuo* near to the poles of very powerful magnets, yet have not been able to observe the least attractive or repulsive force.

63. I have also arranged a fine slip of gold-leaf very near to a bar of copper, the two being in metallic contact by mercury at their extremities. These have been placed *in vacuo,* so that metal rods connected with the extremities of the arrangement should pass through the sides of the vessel into the air. I have then moved powerful magnetic poles, about this arrangement, in various directions, the metallic circuit on the outside being sometimes completed by wires and sometimes broken. But I never could obtain any sensible motion of the gold-leaf, either directed to the magnet or towards the collateral bar of copper, which must have been, as far as induction was concerned, in a similar state to itself.

64. In some cases it has been supposed that, under such circumstances, attractive and repulsive forces have been exhibited, *i. e.,* that such bodies have become slightly magnetic. But the phenomena now described, in conjunction with the confidence we may reasonably repose in M. Ampère's theory of magnetism,

tend to throw doubt on such cases; for if magnetism depend upon the attraction of electrical currents, and if the powerful currents at first excited, both by volta-electric and magneto-electric induction, instantly and naturally cease (12, 28, 47), causing at the same time an entire cessation of magnetic effects at the galvanometer needle, then there can be little or no expectation that any substances not partaking of the peculiar relation in which iron, nickel, and one or two other bodies, stand, should exhibit magneto-attractive powers. It seems far more probable, that the extremely feeble permanent effects observed have been due to traces of iron, or perhaps some other unrecognized cause not magnetic.

65. This peculiar condition exerts no retarding or accelerating power upon electrical currents passing through metal thus circumstanced (20, 33). Neither could any such power upon the inducing current itself be detected; for when masses of metal, wires, helices, etc., were arranged in all possible ways by the side of a wire or helix, carrying a current measured by the galvanomter (20), not the slightest permanent change in the indication of the instrument could be perceived. Metal in the supposed peculiar state, therefore, conducts electricity in all directions with its ordinary facility, or in other words, its conducting power is not sensibly altered by it.

66. All metals take on the peculiar state. This is proved in the preceding experiments with copper and iron (9), and with gold, silver, tin, lead, zinc, antimony, bismuth, mercury, etc., by experiments to be described in the fourth part (132), admitting of easy application. With regard to iron, the experiments prove the thorough and remarkable independence of these phenomena of induction, and the ordinary magnetical appearances of that metal.

67. This state is altogether the effect of the induction exerted, and ceases as soon as the inductive force is removed. It is the same state, whether produced by the collateral passage of voltaic currents (26), or the formation of a magnet (34, 36), or the mere approximation of a magnet (39, 50); and is a strong proof in addition to those advanced by M. Ampère, of the identity of the agents concerned in these several operations. It probably occurs momentarily, during the passage of the common electric spark (24), and may perhaps be obtained hereafter in

bad conductors by weak electrical currents or other means (74, 76).

68. The state appears to be instantly assumed (12), requiring hardly a sensible portion of time for that purpose. The *difference* of time between volta-electric and magneto-electric induction, rendered evident by the galvanometer (59), may probably be thus explained. When a voltaic current is sent through one of two parallel wires, as those of the hollow helix (34), a current is produced in the other wire, as brief in its continuance as the time required for a single action of this kind, and which, by experiment, is found to be inappreciably small. This action will seem still more instantaneous, because, as there is an accumulation of power in the poles of the battery before contact, the first rush of electricity in the wire of communication is greater than that sustained after the contact is completed; the wire of induction becomes at the moment electro-tonic to an equivalent degree, which the moment after sinks to the state in which the continuous current can sustain it, but in sinking, causes an opposite induced current to that at first produced. The consequence is, that the first induced wave of electricity more resembles that from the discharge of an electric jar, than it otherwise would do.

69. But when the iron cylinder is put into the same helix (34), previous to the connexion being made with the battery, then the current from the latter may be considered as active in inducing innumerable currents of a similar kind to itself in the iron, rendering it a magnet. This is known by experiment to occupy time; for a magnet so formed, even of soft iron, does not rise to its fullest intensity in an instant, and it may be because the currents within the iron are successive in their formation or arrangement. But as the magnet can induce, as well as the battery current, the combined action of the two continues to evolve induced electricity, until their joint effect is at a maximum, and thus the existence of the deflecting force is prolonged sufficiently to overcome the inertia of the galvanometer needle.

70. In all these cases where the helices or wires are advanceed towards or taken from the magnet (50, 55), the direct or inverted current of induced electricity continues for the time occupied in the advance or recession; for the electro-tonic state is rising to a higher or falling to a lower degree during that time,

and the change is accompanied by its corresponding evolution of electricity; but these form no objections to the opinion that the electro-tonic state is instantly assumed.

71. This peculiar state appears to be a state of tension, and may be considered as *equivalent* to a current of electricity, at least equal to that produced either when the condition is induced or destroyed. The current evolved, however, first or last, is not to be considered a measure of the degree of tension to which the electro-tonic state has risen; for as the metal retains its conducting powers unimpaired (65) and as the electricity evolved is but for a moment, the peculiar state being instantly assumed and lost (68), the electricity which may be led away by long wire conductors, offering obstruction in their substance proportionate to their small lateral and extensive linear dimensions, can be but a very small portion of that really evolved within the mass at the moment it assumes this condition. Insulated helices and portions of metal instantly assumed the state; and no traces of electricity could be discovered in them, however quickly the contact with the electrometer was made, after they were put under induction, either by the current from the battery or the magnet. A single drop of water or a small piece of moistened paper (23, 56) was obstacle sufficient to stop the current through the conductors, the electricity evolved returning to a state of equilibrium through the metal itself, and consequently in an unobserved manner.

72. The tension of this state may therefore be comparatively very great. But whether great or small it is hardly conceivable that it should exist without exerting a reaction upon the original inducing current, and producing equilibrium of some kind. It might be anticipated that this would give rise to a retardation of the original current; but I have not been able to ascertain that this is the case. Neither have I in any other way as yet been able to distinguish effects attributable to such a reaction.

73. All the results favour the notion that the electro-tonic state relates to the particles, and not to the mass, of the wire or substance under induction, being in that respect different to the induction exerted by electricity of tension. If so, that state may be assumed in liquids when no electrical current is sensible, and even in non-conductors; the current itself, when it occurs, being as it were a contingency due to the existence of conducting

power, and the momentary propulsive force exerted by the particles during their arrangement. Even when conducting power is equal, the currents of electricity, which as yet are the only indicators of this state, may be unequal, because of differences as to number, size, electrical condition, etc., etc., in the particles themselves. It will only be after the laws which govern this new state are ascertained, that we shall be able to predict what is the true condition of, and what are the electrical results obtainable from, any particular substance.

74. The current of electricity which induces the electro-tonic state in a neighboring wire, probably induces that state also in its own wire; for when by a current in one wire a collateral wire is made electro-tonic, the latter state is not rendered any way incompatible or interfering with a current of electricity passing through it (62). If, therefore, the current were sent through the second wire instead of the first it does not seem probable that its inducing action upon the second would be less, but on the contrary more, because the distance between the agent and the matter acted upon would be very greatly diminished. A copper bolt had its extremities connected with a galvanometer, and then the poles of a battery of one hundred pairs of plates connected with the bolt, so as to send the current through it; the voltaic current was then suddenly broken, and the galvanometer observed for any indications of a return current through the copper bolt due to the discharge of its supposed electro-tonic state. No effect of the kind was obtained, nor indeed, for two reasons, ought it to be expected; for first, as the cessation of induction and the discharge of the electro-tonic condition are simultaneous, and not successive, the return current would only be equivalent to the neutralization of the last portion of the inducing current, and would not therefore show any alteration of direction; or assuming that time did intervene, and that the latter current was really distinct from the former, its short, sudden character (12, 26) would prevent it from being thus recognized.

75. No difficulty arises, I think, in considering the wire thus rendered electro-tonic by its own current more than by any external current, especially when the apparent non-interference of that state with currents is considered (62, 71). The simultaneous existence of the conducting and electro-tonic states finds an analogy in the manner in which electrical currents can be passed

through magnets, where it is found that both the currents passed, and those of the magnets, preserve all their properties distinct from each other, and exert their mutual actions.

76. The reason given with regard to metals extends also to fluids and all other conductors, and leads to the conclusion that when electric currents are passed through them they also assume the electro-tonic state. Should that prove to be the case its influence in voltaic decomposition, and the transference of the elements to the poles can hardly be doubted. In the electro-tonic state the homogeneous particles of matter appear to have assumed a regular but forced electrical arrangement in the direction of the current, which, if the matter be undecomposable, produces, when relieved, a return current; but in decomposable matter this forced state may be sufficient to make an elementary particle leave its companion, with which it is in a constrained condition, and associate with the neighboring similar particle, in relation to which it is in a more natural condition, the forced electrical arrangement being itself discharged or relieved, at the same time, as effectually as if it had been freed from induction. But as the original voltaic current is continued, the electro-tonic state may be instantly renewed, producing the forced arrangement of the compound particles, to be as instantly discharged by a transference of the elementary particles of the opposite kind in opposite directions, but parallel to the current. Even the differences between common and voltaic electricity, when applied to effect chemical decomposition, which Dr. Wollaston has pointed out,* seem explicable by the circumstances connected with the induction of electricity from these two sources (25). But as I have reserved this branch of inquiry, that I might follow out the investigations contained in the present paper, I refrain (though much tempted) from offering further speculations.

[*Four paragraphs are omitted.*]

§ 4. *Explication of Arago's Magnetic Phenomena*

81. If a plate of copper be revolved close to a magnetic needle, or magnet, suspended in such a way that the latter may rotate in a plane parallel to that of the former, the magnet tends to follow the motion of the plate; or if the magnet be revolved, the

* *Philosophical Transactions*, 1801, p. 247.

plate tends to follow its motion; and the effect is so powerful, that magnets or plates of many pounds weight may be thus carried round. If the magnet and plate be at rest relative to each other, not the slightest effect, attractive or repulsive, or of any kind, can be observed between them (62). This is the phenomenon discovered by M. Arago; and he states that the effect takes place not only with all metals, but with solids, liquids, and even gases, *i. e.,* with all substances (130).

82. Mr. Babbage and Sir John Herschel, on conjointly repeating the experiments in this country,* could obtain the effects only with the metals, and with carbon in a peculiar state (from gas retorts), *i. e.,* only with excellent conductors of electricity. They refer the effect to magnetism induced in the plate by the magnet; the pole of the latter causing an opposite pole in the nearest part of the plate, and round this a more diffuse polarity of its own kind (120). The essential circumstance in producing the rotation of the suspended magnet is, that the substance revolving below it shall acquire and lose its magnetism in sensible time and not instantly (124). This theory refers the effect to an attractive force, and is not agreed to by the discoverer, M. Arago, nor by M. Ampère, who quote against it the absence of all attraction when the magnet and metal are at rest (62, 126), although the induced magnetism should still remain; and who, from experiments made with a long dipping needle conceive the action to be always repulsive (125).

83. Upon obtaining electricity from magnets by the means already described (36, 46), I hoped to make the experiment of M. Arago a new source of electricity; and did not despair, by reference to terrestrial magneto-electric induction, of being able to construct a new electrical machine. Thus stimulated, numerous experiments were made with the magnet of the Royal Society at Mr. Christie's house, in all of which I had the advantage of his assistance. As many of these in the course of the investigation were superseded by more perfect arrangements, I shall consider myself at liberty to rearrange them in a manner calculated to convey most readily what appears to me to be a correct view of the nature of the phenomena.

84. The magnet has been already described (44). To concentrate the poles, and bring them nearer to each other, two iron

* *Philosophical Transactions,* 1825, p. 467.

or steel bars, each about six or seven inches long, one inch wide, and half an inch thick, were put across the poles as in Fig. 7, and being supported by twine from slipping, could be placed as near to or far from each other as was required. Occasionally two bars of soft iron were employed, so bent, that when applied, one to each pole, the two smaller resulting poles were vertically over each other, either being uppermost at pleasure.

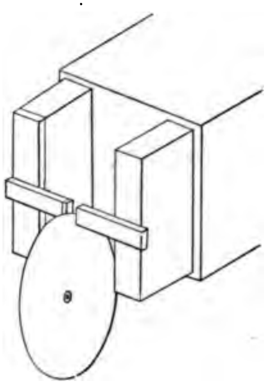
FIG. 7.

85. A disc of copper, twelve inches in diameter, and about one fifth of an inch in thickness, fixed upon a brass axis, was mounted in frames so as to allow of revolution either vertically or horizontally, its edge being at the same time introduced more or less between the magnetic poles (Fig. 7). The edge of the plate was well amalgamated for the purpose of obtaining a good but movable contact, and a part round the axis was also prepared in a similar manner.

86. Conductors or electric collectors of copper and lead were constructed so as to come in contact with the edge of the copper disc (85), or with other forms of plates hereafter to be described (101). These conductors were about four inches long, one third of an inch wide, and one fifth of an inch thick; one end of each was slightly grooved, to allow of more exact adaptation to the somewhat convex edge of the plates, and then amalgamated. Copper wires, one sixteenth of an inch in thickness, attached, in the ordinary manner, by convolutions to the other ends of these conductors, passed away to the galvanometer.

87. The galvanometer was roughly made, yet sufficiently delicate in its indications. The wire was of copper covered with silk, and made sixteen or eighteen convolutions. Two sewing needles were magnetized and fixed on to a stem of dried grass parallel to each other, but in opposite directions, and about half an inch apart; this system was suspended by a fibre of unspun silk, so that the lower needle should be between the convolutions of the multiplier, and the upper above them. The latter was by

much the most powerful magnet, and gave terrestrial direction to the whole; Fig. 8 represents the direction of the wire and of the needles when the instrument was placed in the magnetic meridian: the ends of the wires are marked A and B for convenient reference hereafter. The letters S and N designate the south and north ends of the needle when affected merely by territorial magnetism; the end N is therefore the marked pole (44). The whole instrument was protected by a glass jar, and stood, as to position and distance relative to the large magnet, under the same circumstances as before (45).

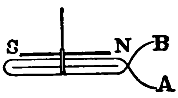

FIG. 8.

88. All these arrangements being made, the copper disc was adjusted as in Fig. 7, the small magnetic poles being about half an inch apart, and the edge of the plate inserted about half their width between them. One of the galvanometer wires was passed twice or thrice loosely round the brass axis of the plate, and the other attached to a conductor (86), which itself was retained by the hand in contact with the amalgamated edge of the disc at the part immediately between the magnetic poles. Under these circumstances all was quiescent, and the galvanometer exhibited no effect. But the instant the plate moved, the galvanometer was influenced, and by revolving the plate quickly the needle could be deflected 90° or more.

89. It was difficult under the circumstances to make the contact between the conductor and the edge of the revolving disc uniformly good and extensive; it was also difficult in the first experiments to obtain a regular velocity of rotation; both these causes tended to retain the needle in a continual state of vibration; but no difficulty existed in ascertaining to which side it was deflected, or generally, about what line it vibrated. Afterwards, when the experiments were made more carefully, a permanent deflection of the needle of nearly 45° could be sustained.

90. Here therefore was demonstrated the production of a permanent current of electricity by ordinary magnets (57).

91. When the motion of the disc was reversed, every other circumstance remaining the same, the galvanometer needle was deflected with equal power as before; but the deflection was on the opposite side, and the current of electricity evolved, therefore, the reverse of the former. [*Six paragraphs are omitted.*]

98. All care was taken to render these results independent of the earth's magnetism, or of the mutual magnetism of the magnet and galvanometer needles. The contacts were made in the magnetic equator of the plate, and at other parts; the plate was placed horizontally, and the poles vertically; and other precautions were taken. But the absence of any interference of the kind referred to, was readily shown by the want of all effect when the disc was removed from the poles, or the poles from the disc; every other circumstance remaining the same.

99. The *relation of the current* of electricity produced, to the magnetic pole, to the direction of rotation of the plate, etc., etc., may be expressed by saying, that when the unmarked pole (44, 84) is beneath the edge of the plate, and the latter revolves horizontally, screw-fashion, the electricity which can be collected at the edge of the plate nearest to the pole is positive. As the pole of the earth may be mentally considered as the unmarked pole, this relation of the rotation, the pole, and the electricity evolved, is not difficult to remember. Or if, in Fig. 15, the circle represent the copper disc revolving in the direction of the arrows, and *a* the outline of the unmarked pole placed beneath the plate, then the electricity collected at *b* and the neighboring parts is positive, whilst that collected at the centre *c* and other parts is negative (88). The currents in the plates are therefore from the centre by the magnetic poles towards the circumference.

[*One paragraph is omitted.*]

101. It is now evident that the rotating plate is merely another form of the simpler experiment of passing a piece of metal

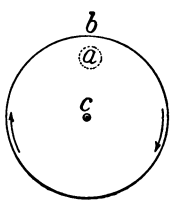

FIG. 15.

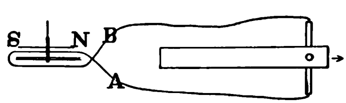

FIG. 16.

between the magnetic poles in a rectilinear direction, and that in such cases currents of electricity are produced at right angles to the direction of the motion, and crossing it at the place of the

magnetic pole or poles. This was sufficiently shown by the following simple experiment: A piece of copper plate one-fifth of an inch thick, one inch and a half wide, and twelve inches long, being amalgamated at the edges, was placed between the magnetic poles, whilst the two conductors from the galvanometer were held in contact with its edges; it was then drawn through between the poles of the conductors in the direction of the arrow, Fig. 16; immediately the galvanometer needle was deflected, its north or marked end was passed eastward, indicating that the wire A received negative and the wire B positive electricity; and as the marked pole was above, the result is in perfect accordance with the effect obtained by the rotatory plate (99).

102. On reversing the motion of the plate, the needle at the galvanometer was deflected in the opposite direction, showing an opposite current.

[*Six paragraphs are omitted.*]

109. When a mere wire, connected with the galvanometer so as to form a complete circuit, was passed through between the poles, the galvanometer was affected; and upon moving the wire to and fro, so as to make the alternate impulses produced correspond with the vibrations of the needle, the latter could be increased to 20° or 30° on each side of the magnetic meridian.

110. Upon connecting the ends of a plate of metal with the galvanometer wires, and then carrying it between the poles from end to end (as in Fig. 23), in either direction, no effect what-

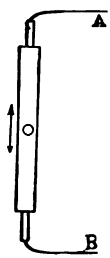

FIG. 23.

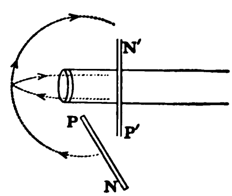

FIG. 24.

ever was produced upon the galvanometer. But the moment the motion became transverse, the needle was deflected.

111. These effects were also obtained from *electro-magnetic* poles, resulting from the use of copper helices or spirals, either

alone or with iron cores (34, 54). The directions of the motions were precisely the same; but the action was much greater when the iron cores were used than without.

[*Two paragraphs are omitted.*]

114. The relation which holds between the magnetic pole, the moving wire or metal, and the direction of the current evolved, *i. e., the law* which governs the evolution of electricity by magneto-electric induction, is very simple, though rather difficult to express. If in Fig. 24 PN represent a horizontal wire passing by a marked magnetic pole, so that the direction of its motion shall coincide with the curved line proceeding from below upwards; or if its motion parallel to itself be in a line tangential to the curved line, but in the general direction of the arrows; or if it pass the pole in other directions, but so as to cut the magnetic curves* in the same general direction, or on the same side as they would be cut by the wire if moving along the dotted curved line; — then the current of electricity in the wire is from P to N. If it be carried in the reverse directions, the electric current will be from N to P. Or if the wire be in the vertical position, figured P′N′, and it be carried in similar directions coinciding with the dotted horizontal curve so far as to cut the magnetic curves on the same side with it, the current will be from P′ to N′. If the wire be considered a tangent to the curved surface of the cylindrical magnet, and it be carried round that surface into any other position, or if the magnet itself be revolved on its axis, so as to bring any part opposite to the tangential wire, — still, if afterwards, the wire be moved in the directions indicated, the current of electricity will be from P to N; or if it be moved in the opposite direction from N to P; so, that as regards the motions of the wire past the pole, they may be reduced to two, directly opposite to each other, one of which produces a current from P to N, and the other from N to P.

115. The same holds true of the unmarked pole of the magnet, except that if it be substituted for the one in the figure, then, as the wires are moved in the direction of the arrows, the cur-

* By magnetic curves I mean the lines of magnetic forces, however modified by the juxtaposition of poles, which would be depicted by iron filings; or those to which a very small magnetic needle would form a tangent.

rent of electricity would be from N to P, and when they move in the reverse direction from P to N.

116. Hence the current of electricity which is excited in the metal when moving in the neighborhood of a magnet, depends for its direction altogether upon the relation of the metal to the resultant of magnetic action, or to the magnetic curves, and may

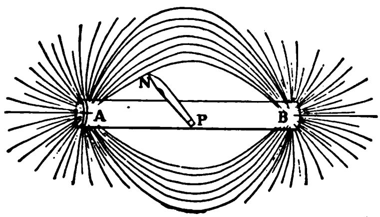

FIG. 25.

be expressed in a popular way, thus: Let AB (Fig. 25) represent a cylinder magnet, A being the marked pole, and B the unmarked pole; let PN be a silver knife-blade resting across the magnet with its edge upward, and with its marked or notched side toward the pole A; then in whatever direction or position this knife be moved edge foremost, either about the marked or the unmarked pole, the current of electricity produced will be from P to N, provided the intersected curves proceeding from A abut upon the notched surface of the knife, and those from B upon the unnotched side. Or if the knife be moved with its back foremost, the current will be from N to P in every possible position and direction, provided the intersected curves abut on the same surface as before. A little model is easily constructed, by using a cylinder of wood for a magnet, a flat piece for the blade, and a piece of thread connecting one end of the cylinder with the other, and passing through a hole in the blade, for the magnetic curves: this readily gives the result of any possible direction.

[*Thirty-two paragraphs are omitted.*]

EXPERIMENTAL RESEARCHES IN ELECTRICITY

By MICHAEL FARADAY

SECOND SERIES

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SECOND SERIES

THE BAKERIAN LECTURE

§ 5. TERRESTRIAL MAGNETO–ELECTRIC INDUCTION. § 6. FORCE AND DIRECTION OF MAGNETO–ELECTRIC INDUCTION GENERALLY

Read Jan. 12, 1832

§ 5. *Terrestrial Magneto-Electric Induction*

149. Guided by the law already expressed (114), I expected that all the electric phenomena of the revolving metal plate could now be produced without any other magnet than the earth. The plate so often referred to (85) was therefore fixed so as to rotate in a horizontal plane. The magnetic curves of the earth (114, *note*), *i. e.,* the dip, passes through this plane at angles of about 70°, which it was expected would be an approximation to perpendicularity, quite enough to allow of magneto-electric induction sufficiently powerful to produce a current of electricity.

150. Upon rotation of the plate, the currents ought, according to the law (114, 121), to tend to pass in the direction of the radii, through *all* parts of the plate, either from the centre to the circumference, or from the circumference to the centre, as the direction of the rotation of the plate was one way or the other. One of the wires of the galvanometer was therefore brought in contact with the axis of the plate, and the other attached to a leaden collector or conductor (86), which itself was placed against the amalgamated edge of the disc. On rotating the plate there was a distinct effect at the galvanometer needle; on reversing the rotation, the needle went in the opposite direction; and by making the action of the plate coincide with the vibrations of the needle, the arc through which the latter passed soon extended to half a circle. [*Eight sections are omitted.*]

159. I have rather, however, been desirous of discovering new facts and new relations dependent upon magneto-electric induc-

tion, than that of exalting the force of those already obtained; being assured that the latter would find their full development hereafter. [*Eleven sections are omitted.*]

171. A piece of common copper wire, about eight feet long, and one twentieth of an inch in thickness, had one of its ends fastened to one of the terminations of the galvanometer wire, and the other end to the other termination; thus it formed an endless continuation of the galvanometer wire: it was then roughly adjusted into the shape of a rectangle, or rather of a loop, the upper part of which could be carried to and fro over the galvanometer, whilst the lower part, and the galvanometer attached to it, remained steady (Fig. 30). Upon moving this loop over the galvanometer from right to left, the magnetic needle was immediately deflected; upon passing the loop back again, the needle passed in the contrary direction to what it did before; upon repeating these motions of the loop in accordance with the vibrations of the needle (39), the latter soon swung through 90° or more.

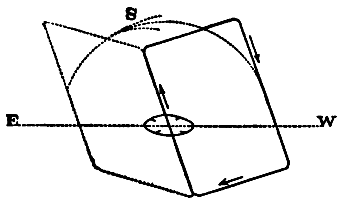

FIG. 30.

172. The relation of the current of electricity produced in the wire, to its motion, may be understood by supposing the convolutions of the galvanometer away, and the wire arranged as a rectangle, with its lower edge horizontal and in the plane of the magnetic meridian, and a magnetic needle suspended above and over the middle part of this edge, and directed by the earth (Fig. 30). On passing the upper part of the rectangle from west to east in the position represented by the dotted line, the marked pole of the magnetic needle went west; the electric current was therefore from north to south in the part of the wire passing under the needle, and from south to north in the moving or upper part of the parallelogram. On passing the upper part of the rectangle from east to west over the galvanometer, the marked pole of the needle went east, and the current of electricity was therefore the reverse of the former.

173. When the rectangle was arranged in a plane east and west, and the magnetic needle made parallel to it, either by the torsion

of its suspension thread or the action of a magnet, still the general effects were the same. On moving the upper part of the rectangle from north to south, the marked pole of the needle went north; when the wire was moved in the opposite direction, the marked pole went south. The same effect took place when the motion of the wire was in any other azimuth of the line of dip; the direction of the current always being conformable to the law formerly expressed (114), and also to the directions obtained with the rotating ball (164).

174. In these experiments it is not necessary to move the galvanometer or needle from its first position. It is quite sufficient if the wire of the rectangle is distorted where it leaves the instrument, and bent so as to allow the moving upper part to travel in the desired direction. [*Five sections are omitted.*]

180. The facility with which electric currents are produced in metals when moving under the influence of magnets, suggests that henceforth precautions should always be taken, in experiments upon metals and magnets, to guard against such effects. Considering the universality of the magnetic influence of the earth, it is a consequence which appears very extraordinary to the mind, that scarcely any piece of metal can be moved in contact with others, either at rest, or in motion with different velocities or in varying directions, without an electric current existing within them. It is probable that amongst arrangements of steam engines and metal machinery, some curious accidental magneto-electric combinations may be found, producing effects which have never been observed, or, if noticed, have never as yet been understood. [*Twelve sections are omitted.*]

§ 6. *General Remarks and Illustrations of the Force and Direction of Magneto-Electric Induction*

[*Eleven sections are omitted.*]

204. Experiments are therefore made in which different metals insulated from each other were passed between the poles of the magnet, their opposite ends being connected with the same end of the galvanometer wire, so that the currents formed and led away to the galvanometer should oppose each other; and when considerable lengths of different wires were used, feeble deflections were obtained.

205. To obtain perfectly satisfactory results a new galvanometer was constructed, consisting of two independent coils, each containing eighteen feet of silked copper wire. These coils were exactly alike in shape and number of turns, and were fixed side by side with a small interval between them, in which a double needle could be hung by a fibre of silk exactly as in the former instrument (87). The coils may be distinguished by the letters K L, and when electrical currents were sent through them in the same direction, acted upon the needle with the sum of their powers; when in opposite directions, with the difference of their powers.

206. The compound helix (199.8.) was now connected, the ends A and B of the iron with A and B ends of galvanometer coil K, and the ends A and B of the copper with B and A ends of galvanometer coil L, so that the currents excited in the two helices, should pass in opposite directions through the coils K and L. On introducing a small cylinder magnet within the helices, the galvanometer needle was powerfully deflected. On disuniting the iron helix, the magnet caused with the copper helix alone still stronger deflection in the same direction. On reuniting the iron helix, and unconnecting the copper helix, the magnet caused a moderate deflection in the contrary direction. Thus it was evident that the electric current induced by a magnet in a copper wire was far more powerful than the current induced by the same magnet in an equal iron wire.

207. To prevent any error that might arise from the greater influence, from vicinity or other circumstances, of one coil on the needle beyond that of the other, the iron and copper terminations were changed relative to the galvanometer coils K L, so that the one which before carried the current from the copper now conveyed that from the iron, and vice versa. But the same striking superiority of the copper was manifested as before. This precaution was taken in the rest of the experiments with other metals to be described.

208. I then had wires of iron, zinc, copper, tin, and lead, drawn to the same diameter (very nearly one-twentieth of an inch), and I compared exactly equal lengths, namely, sixteen feet, of each in pairs in the following manner: The ends of the copper wire were connected with the ends A and B of galvanometer coil K, and the ends of the zinc wire with the terminations

A and B of the galvanometer coil L. The middle part of each wire was then coiled six times round a cylinder of soft iron covered with paper, long enough to connect the poles of Daniell's horseshoe magnet (50), (Fig. 33), so that similar helices of copper and zinc, each of six turns, surrounded the bar at two places equidistant from each other and from the poles of the magnet; but these helices were purposely arranged so as to be in contrary directions, and therefore send contrary currents through the galvanometer coils K and L.

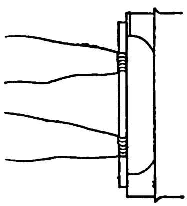

FIG. 33.

209. On making and breaking contact between the soft iron bar and the poles of the magnet, the galvanometer was strongly affected; on detaching the zinc it was still more strongly affected in the same direction. On taking all the precautions before alluded to (207), with others, it was abundantly proved that the current induced by the magnet in copper was far more powerful than in zinc.

210. The copper was then compared in a similar manner with tin, lead, and iron, and surpassed them all, even more than it did zinc. The zinc was then compared experimentally with the tin, lead and iron and found to produce a more powerful current than any of them. Iron in the same manner proved superior to tin and lead. Tin came next, and lead the last.

211. Thus the order of these metals is copper, zinc, iron, tin and lead. It is exactly their order with respect to conducting power for electricity, and, with the exception of iron, is the order presented by the magneto-rotation experiments by Messrs. Babbage, Herschel, Harris, &c. The iron has additional power in the latter kind of experiments, because of its ordinary magnetic relations, and its place relative to magneto-electric action of the kind now under investigation cannot be ascertained by such trials. In the manner above described it may be correctly ascertained.*

* Mr. Christie, who being appointed reporter upon this paper, had it in his hands before it was complete, felt the difficulty (202); and to satisfy his mind, made experiments upon iron and copper with the large magnet (44) and came to the same conclusions as I have arrived at. The two sets of experiments were perfectly independent of each other, neither of us being aware of the other's proceedings.

212. It must still be observed that in these experiments the whole effect between different metals is not obtained; for of the thirty-four feet of wire included in each circuit, eighteen feet are copper in both, being the wire of the galvanometer coils; and as the whole circuit is concerned in the resulting force of the current, this circumstance must tend to diminish the difference which would appear between the metals if the circuits were of the same substances throughout. In the present case the difference obtained is probably not more than a half of that which would be given if the whole of each circuit were of one metal.

213. These results tend to prove that the currents produced by magneto-electric induction in bodies are proportional to their conducting power. That they are exactly proportional to and altogether dependent upon the conducting power, is, I think, proved by the perfect neutrality displayed when two metals or other substances, as acid, water, etc., etc. (201, 186), are opposed to each other in their action. The feeble current which tends to be produced in the worse conductor, has its transmission favored in the better conductor, and the stronger current which tends to form in the latter has its intensity diminished by the obstruction of the former, and the forces of generation and obstruction are so perfectly balanced as to neutralize each other exactly. Now as the obstruction is inversely as the conducting power, the tendency to generate a current must be directly as that power to produce this perfect equilibrium.

214. The cause of the equality of action under the various circumstances described, where great extent of wire (183) or wire and water (184) were connected together, which yet produced such different effects upon the magnet, is now evident and simple.

215. The effects of a rotating substance upon a needle or magnet ought, where ordinary magnetism has no influence, to be directly as the conducting power of the substance; and I venture now to predict that such will be found to be the case; and that in all those instances where non-conductors have been supposed to exhibit this peculiar influence, the motion has been due to some interfering cause of an ordinary kind; as mechanical communication of motion through the parts of the apparatus or otherwise (as in the case Mr. Harris has pointed out*); or else

* *Philosophical Transactions*, 1831, p. 68.

to ordinary magnetic attractions. To distinguish the effects of the latter from those of the induced electric currents, I have been able to devise a most perfect test, which shall be almost immediately described (243).

216. There is every reason to believe that the magnet or magnetic needle will become an excellent measure of the conducting power of substances rotated near it; for I have found by careful experiment, that when a constant current of electricity was sent successively through a series of wires of copper, platina, zinc, silver, lead, and tin, drawn to the same diameter, the deflection of the needle was exactly equal by them all. It must be remembered that when bodies are rotated in a horizontal plane, the magnetism of the earth is active upon them. As the effect is general to the whole of the plate, it may not interfere in these cases; but in some experiments and calculations may be of important consequence.

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217. Another point which I endeavored to ascertain, was, whether it was essential or not that the moving part of the wire should, in cutting the magnetic curves, pass into positions of greater or lesser magnetic force; or whether, always intersecting curves of equal magnetic intensity, the mere motion was sufficient for the production of the current. That the latter is true, has been proved already in several of the experiments on terrestrial magneto-electric induction. Thus the electricity evolved from the copper plate (149), the currents produced in the rotating globe (161, etc.), and those passing through the moving wire (171), are all produced under circumstances in which the magnetic force could not but be the same during the whole experiments.

218. To prove the point with an ordinary magnet, a copper disc was cemented upon the end of a cylinder magnet, with paper intervening; the magnet and disc were rotated together, and collectors (attached to the galvanometer) brought in contact with the circumference and the central part of the copper plate. The galvanometer needle moved as in former cases, and the *direction* of motion was the *same* as that which would have resulted, if the copper only had revolved, and the magnet been

fixed. Neither was there any apparent difference in the quantity of deflection. Hence, rotating the magnet causes no difference in the results; for a rotatory and a stationary magnet produce the same effect upon the moving copper.

219. A copper cylinder, closed at one extremity, was then put over the magnet, one half of which it inclosed like a cap; it was firmly fixed, and prevented from touching the magnet anywhere by interposed paper. The arrangement was then floated in a narrow jar of mercury, so that the lower edge of the copper cylinder touched the fluid metal; one wire of the galvanometer dipped into this mercury, and the other into a little cavity in the centre of the end of the copper cap. Upon rotating the magnet and its attached cylinder, abundance of electricity passed through the galvanometer, and in the same direction as if the cylinder had rotated only, the magnet being still. The results, therefore, were the same as those with the disc (218).

220. That the metal of the magnet itself might be substituted for the moving cylinder, disc, or wire, seemed an inevitable consequence, and yet one which would exhibit the effects of magneto-electric induction in a striking form. A cylinder magnet had therefore a little hole made in the centre of each end to receive a drop of mercury, and was then floated pole upwards in the same metal contained in a narrow jar. One wire from the galvanometer dipped into the mercury of the jar, and the other into the drop contained in the hole at the upper extremity of the axis. The magnet was then revolved by a piece of string passed round it, and the galvanometer needle immediately indicated a powerful current of electricity. On reversing the order of rotation, the electrical current was reversed. The direction of the electricity was the same as if the copper cylinder (219) or a copper wire had revolved round the fixed magnet in the same direction as that which the magnet itself had followed. Thus a *singular independence* of the magnetism and the bar in which it resides is rendered evident.

221. In the above experiment the mercury reached about half way up the magnet; but when its quantity was increased until within one-eighth of an inch of the top, or diminished until equally near the bottom, still the same effects and the *same direction* of electrical current was obtained. But in those extreme proportions the effect did not appear so strong as when

the surface of the mercury was about the middle, or between that and an inch from each end. The magnet was eight inches and a half long, and three-quarters of an inch in diameter.

222. Upon inversion of the magnet, and causing rotation in the same direction, *i. e.,* always screw or always unscrew, then a contrary current of electricity was produced. But when the motion of the magnet was continued in a direction constant in relation to its *own axis,* then electricity of the same kind was collected at both poles, and the opposite electricity at the equator or in its neighborhood, or in the parts corresponding to it. If the magnet be held parallel to the axis of the earth, with its unmarked pole directed to the pole star, and then rotated so that the parts at its southern side pass from west to east in conformity to the motion of the earth; then positive electricity may be collected at the extremities of the magnet, and negative electricity at or about the middle of its mass.

223. When the galvanometer was very sensible, the mere spinning of the magnet in the air, whilst one of the galvanometer wires touched the extremity, and the other the equatorial parts, was sufficient to evolve a current of electricity and deflect the needle.

224. Experiments were then made with a similar magnet, for the purpose of ascertaining whether any return of the electric current could occur at the central or axial parts, they having the same angular velocity of rotation as the other parts (259); the belief being that it could not.

225. A cylinder magnet, seven inches in length, and three-quarters of an inch in diameter, had a hole pierced in the direction of its axis from one extremity, a quarter of an inch in diameter, and three inches deep. A copper cylinder surrounded by paper and amalgamated at both extremities, was introduced so as to be in metallic contact at the bottom of the hole, by a little mercury, with the middle of the magnet; insulated at the sides by the paper; and projecting about a quarter of an inch above the end of the steel. A quill was put over the copper rod, which reached to the paper, and formed a cup to receive mercury for the completion of the circuit. A high paper edge was also raised round that end of the magnet and mercury put within it, which, however, had no metallic connection with that in the quill, except through the magnet itself and the copper

rod (Fig. 34). The wires A and B from the galvanometer were dipped into these two portions of mercury; any current through them could, therefore, only pass down the magnet towards its equatorial parts, and then up the copper rod; or vice versa.

226. When thus arranged and rotated screw fashion, the marked end of the galvanometer needle went west, indicating that there was a current through the instrument from A to B, and consequently from B through the magnet and copper rod to A (Fig. 34).

227. The magnet was then put into a jar of mercury (Fig. 35) as before (219); the wire A left in contact with the copper axis, but the wire B dipped in the mercury of the jar, and therefore in metallic communication with the equatorial parts

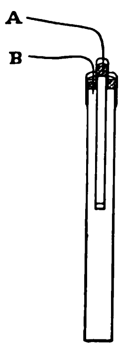

FIG. 34.

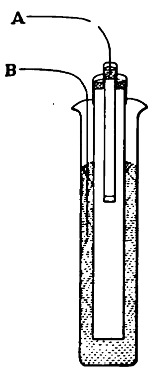

FIG. 35.

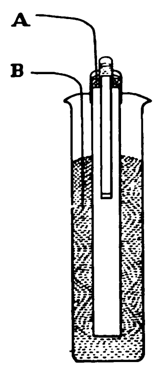

FIG. 36.

of the magnet instead of its polar extremity. On revolving the magnet screw fashion, the galvanometer needle was deflected in the same direction as before, but far more powerfully. Yet it is evident that the parts of the magnet from the equator to the pole were out of the electric circuit.

228. Then the wire A was connected with the mercury on the extremity of the magnet, the wire B still remaining in contact with that in the jar (Fig. 36), so that the copper axis was altogether out of the circuit. The magnet was again revolved screw fashion, and again caused the same deflection of the needle, the current being as strong as it was in the last trial (227), and much stronger than at first (226).

229. Hence it is evident that there is no discharge of the current at the centre of the magnet, for the current, now freely evolved, is up through the magnet; but in the first experiment (226) it was down. In fact, at that time, it was only the part of the moving metal equal to a little disc extending from the end of the wire B in the mercury to the wire A that was efficient, *i. e.,* moving with a different angular velocity to the rest of the circuit (258); and for that portion the direction of the current is consistent with the other results.

230. In the two after-experiments, the *lateral* parts of the magnet or of the copper rod are those which move relative to the other parts of the circuit, *i. e.,* the galvanometer wires; and being more extensive, intersecting more curves, or moving with more velocity, produce the greater effect. For the discal part, the direction of the induced electric current is the same in all, namely, from the circumference towards the centre.

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231. The law under which the induced electric current excited in bodies moving relatively to magnets, is made dependent on the intersection of the magnetic curves by the metal (114) being thus rendered more precise and definite (217, 220, 224), seems now even to apply to the cause in the first section of the former paper (26); and by rendering a perfect reason for the effects produced, take away any for supposing that peculiar condition, which I ventured to call the electro-tonic state (60).

232. When an electrical current is passed through a wire, that wire is surrounded at every part by magnetic curves, diminishing in intensity according to their distance from the wire, and which in idea may be likened to rings situated in planes perpendicular to the wire or rather to the electric current within it. These curves, although different in form, are perfectly analogous to those existing between two contrary magnetic poles opposed to each other; and when a second wire, parallel to that which carries the current, is made to approach the latter (18), it passes through magnetic curves exactly of the same kind as those it would intersect when carried between opposite magnetic poles (109) in one direction; and as it recedes from the inducing wire, it cuts the curves around it in the same manner that it

would do those between the same poles if moved in the other direction.

233. If the wire NP (Fig. 40) have an electric current passed through it in the direction from P to N, then the dotted ring may represent a magnetic curve round it, and it is in such a

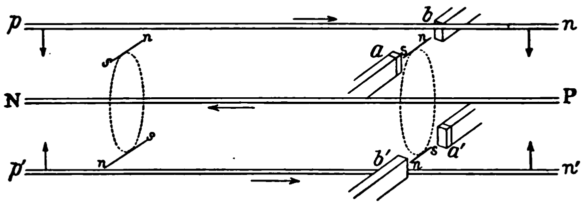

FIG. 40. FIG. 41.

direction that if small magnetic needles be placed as tangents to it, they will become arranged as in the figure, *n* and *s* indicating north and south ends (44, *note*).

234. But if the current of electricity were made to cease for a while, and magnetic poles were used instead to give direction to the needles, and make them take the same position as when under the influence of the current, then they must be arranged as at Fig. 41; the marked and unmarked poles *ab* above the wire, being in opposite directions to those *a'b'* below. In such a position, therefore, the magnetic curves between the poles *ab* and *a'b'* have the same general direction with the corresponding parts of the ring magnetic curve surrounding the wire NP carrying an electric current.

235. If the second wire *pn* (Fig. 40) be now brought towards the principal wire, carrying a current, it will cut an infinity of magnetic curves, similar in direction to that figured, and consequently similar in direction to those between the poles *ab* of the magnets (Fig. 41), and it will intersect these current curves in the same manner as it would the magnet curves, if it passed from above between the poles downwards. Now, such an intersection would, with the magnets, induce an electric current in the wire from *p* to *n* (114); and, therefore, as the curves are alike in arrangement, the same effect ought to result from the intersection of the magnetic curves dependent on the current in the wire NP; and such is the case, for on approximation the in-

duced current is in the opposite direction to the principal current (19).

236. If the wire *p′n′* be carried up from below, it will pass in the opposite direction between the magnetic poles; but then also the magnetic poles themselves are reversed (Fig. 41), and the induced current is therefore (114) still in the same direction as before. It is also, for equally sufficient and evident reasons, in the same direction, if produced by the influence of the curves dependent upon the wire.

237. When the second wire is retained at rest in the vicinity of the principal wire, no current is induced through it, for it is intersecting no magnetic curves. When it is removed from the principal wire, it intersects the curves in the opposite direction to what it did before (235) ; and a current in the opposite direction is induced, which therefore corresponds with the direction of the principal current (19). The same effect would take place if by inverting the direction of motion of the wire in passing between either set of poles (Fig. 41), it were made to intersect the curves there existing in the opposite direction to what it did before.

238. In the first experiments (10, 13), the inducing wire and that under induction were arranged at a fixed distance from each other, and then an electric current sent through the former. In such cases the magnetic curves themselves must be considered as moving (if I may use the expression) across the wire under induction, from the moment at which they begin to be developed until the magnetic force of the current is at its utmost; expanding as it were from the wire outwards, and consequently being in the same relation to the fixed wire under induction, as if it had moved in the opposite direction across them, or towards the wire carrying the current. Hence the first current induced in such cases was in the contrary direction to the principal current (17, 235). On breaking the battery contact, the magnetic curves (which are mere expressions for arranged magnetic forces) may be conceived as contracting upon and returning towards the failing electrical current, and therefore move in the opposite direction across the wire, and cause an opposite induced current to the first.

239. When, in experiments with ordinary magnets, the latter, in place of being moved past the wires, were actually made near

them (27, 36), then a similar progressive development of the magnetic curves may be considered as having taken place, producing the effects which would have occurred by motion of the wires in one direction; the destruction of the magnetic power corresponds to the motion of the wire in the opposite direction.

240. If, instead of intersecting the magnetic curves of a straight wire carrying a current, by approximating or removing a second wire (235), a revolving plate be used, being placed for that purpose near the wire, and, as it were, amongst the magnetic curves, then it ought to have continuous electric currents induced within it; and if a line joining the wire with the centre of the plate were perpendicular to both, then the induced current ought to be, according to the law (114), directly across the plate, from one side to the other, and at right angles to the direction of the inducing current.

241. A single metallic wire one-twentieth of an inch in diameter had an electric current passed through it, and a small copper disc one inch and a half in diameter revolved near to and under, but not in actual contact with it (Fig. 39). Collectors were then applied at the opposite edges of the disc, and the wires from them connected with the galvanometer. As the disc revolved in one direction, the needle was deflected on one side; and when the direction of revolution was reversed, the needle was inclined on the other side, in accordance with the results anticipated.

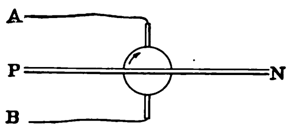

FIG. 39.

242. Thus the reasons which induce me to suppose a particular state in the wire (60) have disappeared; and though it still seems to me unlikely that a wire at rest in the neighborhood of another carrying a powerful electric current is entirely indifferent to it, yet I am not aware of any distinct *facts* which authorize the conclusion that it is in a particular state.

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243. In considering the nature of the cause assigned in these papers to account for the mutual influence of magnets and moving metals (120), and comparing it with that heretofore admitted, namely, the induction of a feeble magnetism like that

produced in iron, it occurred to me that a most decisive experimental test of the two views could be applied (215).

244. No other known power has like direction with that exerted between an electric current and a magnetic pole; it is tangential, while all other forces, acting at a distance, are direct. Hence, if a magnetic pole on one side of a revolving plate follows its course by reason of its obedience to the tangential force exerted upon it by the very current of electricity which it has itself caused, a similar pole on the opposite side of the plate should immediately set it free from this force; for the currents which tend to be formed by the action of the two poles are in opposite directions; or, rather, no current tends to be formed, or no magnetic curves are intersected (114); and therefore the magnet should remain at rest. On the contrary, if the action of a north magnetic pole were to produce a southness in the nearest part of the copper plate, and a diffuse northness elsewhere (82), as is really the case with iron, then the use of another north pole on the opposite side of the same part of the plate should double the effect instead of destroying it, and double the tendency of the first magnet to move with the plate.

245. A thick copper plate (85) was therefore fixed on a vertical axis, a bar magnet was suspended by a plaited silk cord, so that its marked pole hung over the edge of the plate, and a sheet of paper being interposed, the plate was revolved; immediately the magnetic pole obeyed its motion and passed off in the same direction. A second magnet of equal size and strength was then attached to the first, so that its marked pole should hang *beneath* the edge of the copper plate in a corresponding position to that above, and at an equal distance (Fig. 37). Then a paper sheath or screen being interposed as before, and the plate revolved, the poles were found entirely indifferent to its motion, although either of them alone would have followed the course of rotation.

246. On turning one magnet round, so that *opposite* poles were on each side of the plate, then the mutual action of the poles and the moving metal was a maximum.

247. On suspending one magnet so that its axis was level with the plate, and either pole opposite its edge, the revolution of the plate caused no motion of the magnet. The electrical currents dependent upon induction would now tend to be produced

in a vertical direction across the thickness of the plate, but could not be so discharged, or at least only to so slight a degree as to leave all effects insensible; but ordinary magnetic induction, or that on an iron plate, would be equally if not more powerfully developed in such a position (251).

248. Then with regard to the production of electricity in these cases: — whenever motion was communicated by the plate to the magnets, currents existed; when it was not communicated they ceased. A marked pole of a large bar magnet was put under the edge of the plate; collectors (86) applied at the axis and edge of the plate as on former occasions (Fig. 38), and these connected with the galvanometer; when the plate was revolved, abundance of electricity passed to the instrument. The un-

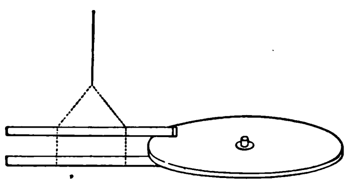


FIG. 37.

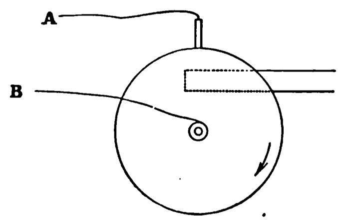


FIG. 38.

marked pole of a similar magnet was then put over the place of the former pole, so that contrary poles were above and below; on revolving the plate, the electricity was more powerful than before. The latter magnet was then turned end for end, so that marked poles were both above and below the plate, and then upon revolving it, scarcely any electricity was procured. By adjusting the distance of the poles so as to correspond with their relative force, they at last were brought so perfectly to neutralize each other's inductive action upon the plate, that no electricity could be obtained with the most rapid motion.

249. I now proceeded to compare the effect of similar and dissimilar poles upon iron and copper, adopting for the purpose Mr. Sturgeon's very useful form of Arago's experiment. This consists in a circular plate of metal supported in a vertical plane by a horizontal axis, and weighted a little at one edge or rendered eccentric so as to vibrate like a pendulum. The poles of the magnets are applied near the side and edges of these plates,

and then the number of vibrations, required to reduce the vibrating arc a certain constant quantity, noted. In the first description of this instrument* it is said that opposite poles produced the greatest retarding effect, and similar poles none; and yet within a page of the place the effect is considered as of the same kind with that produced in iron.

250. I had two such plates mounted, one of copper, one of iron. The copper plate alone gave sixty vibrations, in the average of several experiments, before the arc of vibration was reduced from one constant mark to another. On placing opposite magnetic poles near to, and on each side of the same place, the vibrations were reduced to fifteen. On putting similar poles on each side of it, they rose to fifty; and on placing two pieces of wood of equal size with the poles equally near, they became fifty-two. So that, when similar poles were used, the magnetic effect was little or none (the obstruction being due to the confinement of the air, rather), whilst with opposite poles it was the greatest possible. When a pole was presented to the edge of the plate, no retardation occurred.

251. The iron plate alone made thirty-two vibrations, whilst the arc of vibration diminished a certain quantity. On presenting a magnetic pole to the edge of the plate (247), the vibrations were diminished to eleven; and when the pole was about half an inch from the edge, to five.

252. When the marked pole was put at the side of the iron plate at a certain distance, the number of vibrations was only five. When the marked pole of the second bar was put on the opposite side of the plate at the same distance (250), the vibrations were reduced to two. But when the second pole was an unmarked one, yet occupying exactly the same position, the vibrations rose to twenty-two. By removing the stronger of these two opposite poles a little way from the plate, the vibrations increased to thirty-one, or nearly the original number. But on removing it *altogether,* they fell to between five and six.

253. Nothing can be more clear, therefore, than that with iron, and bodies admitting of ordinary magnetic induction, *opposite* poles on opposite sides of the edge of the plate neutralize each other's effect, whilst *similar* poles exalt the action; a single pole end is also sufficient. But with copper, and sub-

* *Edin. Phil. Journal,* 1825, p. 124.

stances not sensible to ordinary magnetic impressions, *similar* poles on opposite sides of the plate neutralize each other; *opposite* poles exalt the action; and a single pole at the edge or end on does nothing.

254. Nothing can more completely show the thorough independence of the effects obtained with the metals by Arago, and those due to ordinary magnetic forces; and henceforth, therefore, the application of two poles to various moving substances will, if they appear at all magnetically affected, afford a proof of the nature of that affection. If opposite poles produce a greater effect than one pole, the result will be due to electric currents. If similar poles produce more effect than one, then the power is *not* electrical; it is not like that active in the metals and carbon when they are moving, and in most cases will probably be found to be not even magnetical, but the result of irregular causes not anticipated and consequently not guarded against.

255. The result of these investigations tends to show that there are really but very few bodies that are magnetic in the manner of iron. I have often sought for indications of this power in the common metals and other substances; and once in illustration of Arago's objection (82), and in hopes of ascertaining the existence of currents in metals by the momentary approach of a magnet, suspended a disc of copper by a single fibre of silk in an excellent vacuum, and approximated powerful magnets on the outside of the jar, making them approach and recede in unison with a pendulum that vibrated as the disc would do: but no motion could be obtained; not merely, no indication of ordinary magnetic powers, but none of *any electric current* occasioned in the metal by the approximation and recession of the magnet. I therefore venture to arrange substances in three classes as regards their relation to magnets: first, those which are affected when at rest, like iron, nickel, etc., being such as possess ordinary magnetic properties; then, those which are affected when in motion, being conductors of electricity in which are produced electric currents by the inductive force of the magnet; and, lastly, those which are perfectly indifferent to the magnet, whether at rest or in motion.

256. Although it will require further research, and probably close investigation, both experimental and mathematical, before the exact mode of action between a magnet and metal moving relatively to each other is ascertained; yet many of the results appear sufficiently clear and simple to allow of expression in a somewhat general manner. If a terminated wire move so as to cut a magnetic curve, a power is called into action which tends to urge an electric current through it; but this current cannot be brought into existence unless provision be made at the ends of the wire for its discharge and renewal.

257. If a second wire move in the same direction as the first, the same power is exerted upon it, and it is therefore unable to alter the condition of the first: for there appear to be no natural differences among substances when connected in a series, by which, when moving under the same circumstances relative to the magnet, one tends to produce a more powerful electric current in the whole circuit than another (201, 214).

258. But if the second wire move with a different velocity, or in some other direction, then variations in the force exerted take place; and if connected at their extremities, an electric current passes through them.

259. Taking, then, a mass of metal or an endless wire, and referring to the pole of the magnet as a centre of action (which though perhaps not strictly correct may be allowed for facility of expression, at present), if all parts move in the same direction, and with the same angular velocity, and through magnetic curves of constant intensity, then no electric currents are produced. This point is easily observed with masses subject to the earth's magnetism, and may be proved with regard to small magnets; by rotating them, and leaving the metallic arrangements stationary, no current is produced.

260. If one part of the wire or metal cut the magnetic curves, whilst the other is stationary, then currents are produced. All the results obtained with the galvanometer are more or less of this nature, the galvanometer extremity being the fixed part. Even those with the wire, galvanometer, and earth (170), may be considered so without any error in the result.

261. If the motion of the metal be in the same direction, but the angular velocity of its parts relative to the pole of the magnet different, then currents are produced. This is the case in

Arago's experiment, and also in the wire subject to the earth's induction (172), when it was moved from west to east.

262. If the magnet moves not directly to or from the arrangement, but laterally, then the case is similar to the last.

263. If different parts move in opposite directions across the magnetic curves, then the effect is a maximum for equal velocities.

264. All these in fact are variations of one simple condition, namely, that all parts of the mass shall not move in the same direction across the curves, and with the same angular velocity. But they are forms of expression which, being retained in the mind, I have found useful when comparing the consistency of particular phenomena with general results.

Royal Institution,
December 21, 1831

[*Faraday extends his idea of lines of magnetic force and their relation to induced currents in the twenty-eighth and twenty-ninth series of these Researches*, Vol. III.]

EXPERIMENTAL RESEARCHES IN ELECTRICITY

By MICHAEL FARADAY

NINTH SERIES

CONTENTS

NINTH SERIES

§ 15. On the Influence by the Induction of an Electric Current on Itself: — and on the Inductive Action of Electric Currents Generally

Received December 18, 1834. — Read January 29, 1835

1048. The following investigations relate to a very remarkable inductive action of electric currents, or of the different parts of the same current (74), and indicate an immediate connexion between such inductive action and the direct transmission of electricity through conducting bodies, or even that exhibited in the form of a spark.

1049. The inquiry arose out of a fact communicated to me by Mr. Jenkin, which is as follows. If an ordinary wire of short length be used as the medium of communication between the two plates of an electromotor consisting of a single pair of metals, no management will enable the experimenter to obtain an electric shock from this wire; but if the wire which surrounds an electro-magnet be used, a shock is felt each time the contact with the electromotor is broken, provided the ends of the wire be grasped one in each hand.

1050. Another effect is observed at the same time, which has long been known to philosophers, namely that a bright electric spark occurs at the place of disjunction.

1051. A brief account of these results, with some of a corresponding character which I had observed in using long wires, was published in the *Philosophical Magazine** for 1834; and I added to them some observations on their nature. Further investigations led me to perceive the inaccuracy of my first notions and ended in identifying these effects with the phenomena of induction which I had been fortunate enough to develop in the First Series of the *Experimental Researches* (1-59).* Notwith-

* Vol. V., pp. 349, 444.

standing this identity, the extension and the peculiarity of the views respecting electric currents which the results supply, lead me to believe that they will be found worthy of the attention of the Royal Society.

1052. The *electromotor* used consisted of a cylinder of zinc introduced between the two parts of a double cylinder of copper, and preserved from metallic contact in the usual way by corks. The zinc cylinder was eight inches high and four inches in diameter. Both it and the copper cylinder were supplied with stiff wires, surmounted by cups containing mercury; and it was at these cups that contacts of wires, helices, or electro-magnets, used to complete the circuit, were made or broken. These cups I will call G and E throughout the rest of this paper (1079).

1053. Certain *helices* were constructed, some of which it will be necessary to describe. A pasteboard tube had four copper wires, one twenty-fourth of an inch in thickness, wound round it, each forming a helix in the same direction from end to end: the convolutions of each wire were separated by string, and the superposed helices prevented from touching by intervening calico. The lengths of the wires forming the helices were 48, 49.5, 48 and 45 feet. The first and third wires were united together so as to form one consistent helix of 96 feet in length; and the second and fourth wires were similarly united to form a second helix, closely interwoven with the first, and 94.5 feet in length. These helices may be distinguished by the numbers *i* and *ii*. They were carefully examined by a powerful current of electricity and a galvanometer, and found to have no communication with each other.

1054. Another helix was constructed upon a similar pasteboard tube, two lengths of the same copper wire being used, each forty-six feet long. These were united into one consistent helix of ninety-two feet, which therefore was nearly equal in value to either of the former helices, but was not in close inductive association with them. It may be distinguished by the number *iii*.

1055. A fourth helix was constructed of very thick copper wire, being one fifth of an inch in diameter; the length of the wire used was seventy-nine feet, independent of the straight terminal portions.

1056. The principal *electro-magnet* employed consisted of a

* *Philosophical Transactions*, 1832, p. 126.

cylindrical bar of soft iron twenty-five inches long, and one inch and three-quarters in diameter, bent into a ring, so that the ends nearly touched, and surrounded by three coils of thick copper wire, the similar ends of which were fastened together; each of these terminations was soldered to a copper rod, serving as a conducting continuation of the wire. Hence any electric current sent through the wires was divided in the helices surrounding the ring, into three parts, all of which, however, moved in the same direction. The three wires may therefore be considered as representing one wire, of thrice the thickness of the wire really used.

1057. Other electro-magnets could be made at pleasure by introducing a soft iron rod into any of the helices described (1053, etc.).

1058. The *galvanometer* which I had occasion to use was rough in its construction, having but one magnetic needle, and not at all delicate in its indications.

1059. The effects to be considered *depend on the conductor* employed to complete the communication between the zinc and copper plates of the electromotor; and I shall have to consider this conductor under four different forms: as the helix of an electro-magnet (1056); as an ordinary helix (1053, etc.); as a *long* extended wire, having its course such that the parts can exert little or no mutual influence; and as a *short* wire. In all cases the conductor was of copper.

1060. The peculiar effects are best shown by the *electro-magnet* (1056). When it was used to complete the communication at the electromotor, there was no sensible spark on *making* contact, but on *breaking* contact there was a very large and bright spark with considerable combustion of the mercury. Then, again, with respect to the shock: if the hands were moistened in salt and water, and good contact between them and the wires retained, no shock could be felt upon *making* contact at the electrometer, but a powerful one on *breaking* contact.

1061. When the *helix i* or *iii* (1053, etc.) was used as the connecting conductor, there was also a good spark on breaking contact, but none (sensibly) on making contact. On trying to obtain the shock from these helices, I could not succeed at first. By joining the similar ends of *i* and *ii* so as to make the two helices equivalent to one helix, having wire of double thickness,

I could just obtain the sensation. Using the helix of thick wire (1055) the shock was distinctly obtained. On placing the tongue between two plates of silver connected by wires with the parts which the hands had therefore touched (1064), there was a powerful shock on *breaking* contact, but none on *making* contact.

1062. The power of producing these phenomena exists therefore in the simple helix, as in the electro-magnet, although by no means in the same high degree.

1063. On putting a bar of soft iron into the helix, it became an electro-magnet (1057), and its power was instantly and greatly raised. On putting a bar of copper into the helix, no change was produced, the action being that of the helix alone. The two helices *i* and *ii*, made into one helix of twofold length of wire, produced a greater effect than either *i* or *ii* alone.

1064. On descending from the helix to the mere *long wire,* the following effects were obtained. A copper wire 0.18 of an inch in diameter, and 132 feet in length, was laid out upon the floor of the laboratory, and used as the connecting conductor (1059); it gave no sensible spark on making contact, but produced a bright one on breaking contact, yet not so bright as that from the helix (1061). On endeavoring to obtain the electric shock at the moment contact was broken, I could not succeed so as to make it pass through the hands; but by using two silver plates fastened by small wires to the extremity of the principal wires used, and introducing the tongue between those plates, I succeeded in obtaining powerful shocks upon the tongue and gums, and could easily convulse a flounder, an eel, or a frog. None of these effects could be obtained directly from the electromotor, *i. e.,* when the tongue, frog, or fish was in a similar, and therefore comparative manner, interposed in the course of the communication between the zinc and copper plates, separated everywhere else by the acid used to excite the combination, or by air. The bright spark and the shock, produced only on breaking contact, are therefore effects of the same kind as those produced in a higher degree by the helix, and in a still higher degree by the elctro-magnet.

1065. In order to compare an extended wire with a helix, the helix *i,* containing ninety-six feet, and ninety-six feet of the same-sized wire lying on the floor of the laboratory, were used alternately as conductors: the former gave a much brighter

spark at the moment of disjunction than the latter. Again, twenty-eight feet of copper wire were made up into a helix, and being used gave a good spark on disjunction at the electromotor; being then suddenly pulled out and again employed, it gave a much smaller spark than before, although nothing but its spiral arrangement had been changed.

1066. As the superiority of a helix over a wire is important to the philosophy of the effect, I took particular pains to ascertain the fact with certainty. A wire of copper sixty-seven feet long was bent in the middle so as to form a double termination which could be communicated with the electromotor; one of the halves of this wire was made into a helix and the other remained in its extended condition. When these were used alternately as the connecting wire, the helix half gave by much the strongest spark. It even gave a stronger spark than when it and the extended wire were used conjointly as a double conductor.

1067. When a *short wire* is used, *all* these effects disappear. If it be only two or three inches long, a spark can scarcely be perceived on breaking the junction. If it be ten or twelve inches long and moderately thick, a small spark may be more easily obtained. As the length is increased the spark becomes proportionately brighter, until from extreme length the resistance offered by the metal as a conductor begins to interfere with the principal result.

1068. The effect of elongation was well shown thus: 114 feet of copper wire, one eighteenth of an inch in diameter, were extended on the floor and used as a conductor; it remained cold but gave a bright spark on breaking contact. Being crossed so that the two terminations were in contact near the extremities, it was again used as a conductor, only twelve inches now being included in the circuit: the wire became very hot from the greater quantity of electricity passing through it, and yet the spark on breaking contact was scarcely visible. The experiment was repeated with a wire one-ninth of an inch in diameter, and thirty-six feet long with the same results.

1069. That the effects and also the action, in all these forms of the experiment are identical, is evident from the manner in which the former can be gradually raised from that produced by the shortest wire to that of the most powerful electro-magnet: and this capability of examining what will happen by the most

powerful apparatus, and then experimenting for the same results, or reasoning from them, with the weaker arrangements, is of great advantage in making out the true principles of the phenomena.

1070. The action is evidently dependent upon the wire which serves as a conductor; for it varies as that wire varies in its length or arrangement. The shortest wire may be considered as exhibiting the full effect of spark or shock which the electromotor can produce by its own direct power; all the additional force which the arrangement described can excite being due to some affection of the current, either permanent or momentary, in the wire itself. That it is a *momentary* effect, produced only at the instant of breaking contact, will be fully proved (1089, 1100).

1071. No change takes place in the quantity or intensity of the current during the time the latter is *continued,* from the moment after contact is made, up to that previous to disunion, except what depends upon the increased obstruction offered to the passage of the electricity by a long wire as compared to a short wire. To ascertain this point with regard to *quantity,* the helix *i* (1053) and the galvanometer (1058) were both made parts of the metallic circuit used to connect the plates of a small electromotor, and the deflection at the galvanometer was observed; then a soft iron core was put into the helix, and as soon as the momentary effect was over, and the needle had become stationary it was again observed, and found to stand at exactly the same division as before. Thus the quantity passing through the wire when the current was continued was the same either with or without the soft iron, although the peculiar effects occurring at the moment of disjunction were very different in degree under such variation of circumstances.

1072. That the quality of *intensity* belonging to the constant current did not vary with the circumstances favoring the peculiar results under consideration, so as to yield an explanation of those results, was ascertained in the following manner. The current excited by an electromotor was passed through short wires, and its intensity tried by subjecting different substances to its electrolyzing power (912, 966, etc.); it was then passed through the wires of a powerful electro-magnet (1056), and again examined with respect to its intensity by the same means

and found unchanged. Again the constancy of the *quantity* passed in the above experiment (1071) adds further proof that the intensity could not have varied; for had it been increased upon the introduction of the soft iron, there is every reason to believe that the quantity passed in a given time would also have increased.

1073. The fact is, that under many variations of the experiments, the permanent current *loses* in force as the effects upon breaking contact become *exalted.* This is abundantly evident in the comparative experiments with long and short wires (1068); and is still more strikingly shown by the following variation. Solder an inch or two in length of fine platina wire (about one hundredth of an inch in diameter) on to one end of the long communicating wire, and also a similar length of the same platina wire on to one end of the short communication; then in comparing the effects of these two communications, make and break contact between the platina terminations and the mercury of the cup G or E (1079). When the short wire is used, the platina will be *ignited by the constant current,* because of the quantity of electricity, but the spark on breaking contact will be hardly visible; on using the longer communicating wire, which by obstructing will diminish the current, the platina will remain cold whilst the current passes, but give a bright spark at the moment it ceases: thus the strange result is obtained of a diminished spark and shock from the strong current, and increased effects from the weak one. Hence the spark and shock at the moment of disjunction, although resulting from great intensity and quantity of the current *at that moment,* are no direct indicators or measurers of the intensity or quantity of the constant current previously passing, and by which they are ultimately produced.

1074. It is highly important in using the spark as an indication, by its relative brightness, of these effects, to bear in mind certain circumstances connected with its production and appearance (958). An ordinary electric spark is understood to be the bright appearance of electricity passing suddenly through an interval of air, or other badly conducting matter. A voltaic spark is sometimes of the same nature, but generally is due to the ignition and even combustion of a minute portion of a good conductor; and that is especially the case when the electromotor

consists of but one or few pairs of plates. This can be very well observed if either or both of the metallic surfaces intended to touch be solid and pointed. The moment they come in contact the current passes; it heats, ignites, and even burns the touching points, and the appearance is as if the spark passed on making contact, whereas it is only a case of ignition by the current, contact being previously made, and is perfectly analogous to the ignition of a fine platina wire connecting the extremities of a voltaic battery.

1075. When mercury constitutes one or both of the surfaces used, the brightness of the spark is greatly increased. But as this effect is due to the action on, and probable combustion of the metal, such sparks must only be compared with other sparks also taken from mercurial surfaces, and not with such as may be taken, for instance, between surfaces of platina or gold, for then the appearances are far less bright, though the same quantity of electricity be passed. It is not at all unlikely that the commonly occurring circumstance of combustion may affect even the duration of the light; and that sparks taken between mercury, copper, or other combustible bodies, will continue for a period sensibly longer than those passing between platina or gold.

1076. When the end of a short clean copper wire, attached to one plate of an electromotor, is brought down carefully upon a surface of mercury connected with the other plate, a spark, almost continuous, can be obtained. This I refer to a succession of effects of the following nature: first, contact, — then ignition of the touching points, — recession of the mercury from the mechanical results of the heat produced at the place of contact, and the electro-magnetic condition of the parts at the moment,* — breaking of the contact and the production of the peculiar intense effect dependent thereon, — renewal of the contact by the returning surface of the undulating mercury, — and then a repetition of the same series of effects, and that with such rapidity as to present the appearance of a continued discharge. If a long wire or an electro-magnet be used as the connecting conductor instead of a short wire, a similar appearance may be produced by tapping the vessel containing the mercury and making it vibrate; but the sparks do not usually

* *Quarterly Journal of Science*, Vol. XII, p. 420.

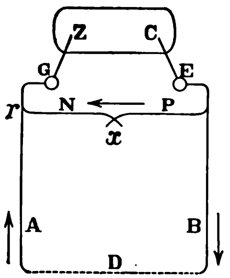
follow each other so rapidly as to produce an apparently continuous spark, because of the time required, when the long wire or electro-magnet is used, both for the full development of the current (1101, 1106) and for its complete cessation.

1077. Returning to the phenomena in question, the first thought that arises in the mind is, that the electricity circulates with something like *momentum or inertia* in the wire, and that thus a long wire produces effects at the instant the current is stopped, which a short wire cannot produce. Such an explanation is, however, at once set aside by the fact, that the same length of wire produces the effects in very different degrees, according as it is simply extended, or made into a helix, or forms the circuit of an electro-magnet (1069). The experiments to be adduced (1089) will still more strikingly show that the idea of momentum cannot apply.

1078. The bright spark at the electromotor, and the shock in the arms appeared evidently to be due to *one* current in the long wire, divided into two parts by the double channel afforded through the body and through the electromotor; for that the spark was evolved at the place of disjunction with the electromotor, not by any direct action of the latter, but by a force immediately exerted in the wire of communication, seemed to be without doubt (1070). It followed, therefore, that by using a better conductor in place of the human body, the *whole* of this extra current might be made to pass at that place; and thus be separated from that which the electromotor could produce by its immediate action, and its *direction* be examined apart from any interference of the original and originating current. This was found to be true; for on connecting the ends of the principal wire together by a cross wire two or three feet in length, applied just where the hands had felt the shock, the whole of the extra current passed by the new channel, and then no better spark than one producible by a short wire was obtained on disjunction at the electromotor.

1079. The *current* thus separated was examined by galvanometers and decomposing apparatus introduced into the course of this wire. I will always speak of it as the current in the cross wire or wires, so that no mistake as to its place or origin may

occur. In the Figure Z and C represent the zinc and copper plates of the electromotor; G and E the cups of mercury where contact is made or broken (1052); A and B the terminations of D, the long wire, the helix, or the electro-magnet, used to complete the circuit; N and P are the cross-wires, which can either be brought into contact at x, or else have a galvanometer (1058) or an electrolyzing apparatus (312, 316) interposed there.



The production of the *shock* from the current in the cross wire, whether D was a long extended wire, or a helix, or an electro-magnet, has been already described (1064, 1061, 1060).

1080. The *spark* of the cross-wire current could be produced at x in the following manner: D was made an electro-magnet; the metallic extremities at x were held close together, or rubbed lightly against each other, whilst contact was broken at G or E. When the communication was perfect at x, little or no spark appeared at G or E. When the condition of vicinity at x was favourable for the result required, a bright spark would pass there at the moment of disjunction, *none* occurring at G and E: this spark was the luminous passage of the extra current through the cross-wires. When there was no contact or passage of current at x, then the spark appeared at G or E, the extra current forcing its way through the electromotor itself. The same results were obtained by the use of the helix or the extended wire at D in place of the electro-magnet.

1081. On introducing a fine platina wire at x, and employing the electro-magnet at D, no visible effects occurred as long as contact was continued; but on breaking the contact at G or E, the fine wire was instantly ignited and fused. A longer and thicker wire could be so adjusted at x as to show ignition, without fusion, every time the contact was broken at G or E.

1082. It is rather difficult to obtain this effect with helices or wires, and for the simple reasons: with the helices *i, ii,* or *iii,* there was such retardation of the electric current, from the length of wire used, that a full inch of platina wire one-fiftieth of an inch in diameter could be retained ignited at the cross-wires during the *continuance of contact,* by the portion of elec-

tricity passing through it. Hence it was impossible to distinguish the particular effects at the moments of making or breaking contact from this constant effect. On using the thick wire helix (1055), the same results ensued.

1083. Proceeding upon the known fact that electric currents of great quantity but low intensity, though able to ignite thick wires, cannot produce that effect upon thin ones, I used a very fine platina wire at x, reducing its diameter until a spark appeared at G or E, when contact was broken there. A quarter of an inch of such wire might be introduced at x without being ignited by the *continuance* of contact at G or E; but when contact was broken at either place, this wire became red hot; proving, by this method, the production of the induced current at that moment.

1084. *Chemical decomposition* was next effected by the cross-wire current, an electro-magnet being used at D, and a decomposing apparatus, with solution of iodide of potassium in paper (1079), employed at x. The conducting power of the connecting system A B D was sufficient to carry all the primary current, and consequently no chemical action took place at x during the *continuance* of contact at G and E; but when contact was broken there was instantly decomposition at x. The iodine appeared against the wire N, and not against the wire P; thus demonstrating that the current through the cross-wires, when contact was broken, was in the *reverse direction* to that marked by the arrow, or that which the electromotor would have sent through it.

1085. In this experiment a bright spark occurs at the place of disjunction, indicating that only a small part of the extra current passed the apparatus at x, because of the small conducting power of the latter.

1086. I found it difficult to obtain the chemical effects with the simple helices and wires in consequence of the diminished inductive power of these arrangements, and because of the passage of a strong constant current at x whenever a very active electromotor was used (1082).

1087. The most instructive set of results was obtained, however, when the *galvanometer* was introduced at x. Using an electro-magnet at D, and continuing contact, a current was then indicated by the deflection, proceeding from P to N, in the di-

rection of the arrow; the cross-wire serving to carry one part of the electricity excited by the electromotor, and that part of the arrangement marked ABD, the other and far greater part, as indicated by the arrows. The magnetic needle was then forced back, by pins applied upon opposite sides of its two extremities, to its natural position when uninfluenced by a current; after which, contact being *broken* at G or E, it was deflected strongly in the opposite direction; thus showing in accordance with the chemical effects (1084), that the extra current followed a course in the cross-wires *contrary* to that indicated by the arrow, *i. e.*, contrary to the one produced by the direct action of the electromotor.*

1088. With the *helix* only (1061), these effects could scarcely be observed, in consequence of the smaller inductive force of this arrangement the opposed action from induction in the galvanometer wire itself, the mechanical condition and tension of the needle from the effect of blocking (1087) whilst the current due to continuance of contact was passing round it; and because of other causes. With the *extended wire* (1064) all these circumstances had still greater influence, and therefore allowed less chance of success.

1089. These experiments, establishing as they did, by the quantity, intensity, and even direction, a distinction between the primary or generating current and the extra current, led me to conclude that the latter was identical with the induced current described (6, 26, 74) in the First Series of these Researches, and this opinion I was soon able to bring to proof, and at the same time obtained not the partial (1078) but entire separation of one current from the other.

1090. The double helix (1053) was arranged so that it should form the connecting wire between the plates of the electromotor, it being out of the current, and its ends unconnected. In this condition *i* acted very well and gave a good spark at the time and place of disjunction. The opposite ends of *ii* were then connected together so as to form an endless wire, *i* remaining unchanged; but now *no spark*, or one scarcely sensible, could be

* It was ascertained experimentally that if a strong current were passed through the galvanometer only, and the needle restrained in one direction as above in its natural position, when the current was stopped, no vibration of the needle in the opposite direction took place.

obtained from the latter at the place of disjunction. Then again, the ends of *ii* were held so nearly together that any current running round that helix should be rendered visible as a spark; and in this manner a spark was obtained from *ii* when the junction of *i* with the electromotor was broken, in place of appearing at the disjointed extremity of *i* itself.

1091. By introducing a galvanometer or a decomposing apparatus into the circuit formed by the helix *ii*, I could easily obtain the deflections and decompositions occasioned by the induced current due to the breaking contact at helix *i*, or even to that occasioned by making contact of that helix with the electromotor; the results in both cases indicating the contrary directions of the two induced currents thus produced (26).

1092. All these effects, except those of decomposition, were reproduced by two extended long wires, not having the form of helices, but placed close to each other; and thus it was proved that the *extra current* could be removed from the wire carrying the original current to a neighboring wire, and was at the same time identified, in direction and every other respect, with the current producible by induction (1089). The case, therefore, of the bright spark and shock on disjunction may now be stated thus: If a current be established in a wire, and another wire, forming a complete circuit, be placed parallel to the first, at the moment the current in the first is stopped it induces a current in the *same* direction in the second, the first exhibiting then but a feeble spark; but if the second wire be away, disjunction of the first wire induces a current in itself in the same direction, producing a strong spark. The strong spark in the single long wire or helix, at the moment of disjunction, is therefore the equivalent of the current which would be produced in a neighboring wire if such second current were permitted.

1093. Viewing the phenomena as the results of the induction of electrical currents, many of the principles of action, in the former experiments, become far more evident and precise. Thus the different effects of short wires, long wires, helices, and electro-magnets (1069) may be comprehended. If the inductive action of a wire a foot long upon a collateral wire also a foot in length, be observed it will be found very small; but if the same current be sent through a wire fifty feet long, it will induce in a neighboring wire of fifty feet a far more powerful current at

the moment of making or breaking contact, each successive foot of wire adding to the sum of action, and by parity of reasoning, a similar effect should take place when the conducting wire is also that in which the induced current is formed (74): hence the reason why a long wire gives a brighter spark on breaking contact than a short one (1068), although it carries much less electricity.

1094. If the long wire be made into a helix, it will then be still more effective in producing sparks and shocks on breaking contact; for by the mutual inductive action of the convolutions each aids its neighbor, and will be aided in turn, and the sum of effect will be very greatly increased.

1095. If an electro-magnet be employed, the effect will be still more highly exalted; because the iron magnetized by the power of the continuing current, will lose its magnetism at the moment the current ceases to pass, and in so doing will tend to produce an electric current in the wire around it (37, 38), in conformity with that which the cessation of current in the helix itself also tends to produce.

1096. By applying the laws of the induction of electric currents formerly developed (6, etc.), various new conditions of the experiments could be devised, which by their results should serve as tests of the accuracy of the view just given. Thus, if a long wire be doubled, so that the current in the two halves shall have opposite actions, it ought not to give a sensible spark at the moment of disjunction; and this proved to be the case, for a wire forty feet long covered with silk, being doubled and tied closely together to within four inches of the extremities, when used in that state, gave scarcely a perceptible spark; but being opened out and the parts separated, it gave a very good one. The two helices *i* and *ii* being joined at their similar ends and then used at their other extremities to connect the plates of the electromotor, thus constituted one long helix, of which one half was opposed in direction to the other half: under these circumstances it gave scarcely a sensible spark, even when the soft iron core was within, although containing nearly two hundred feet of wire. When it was made into one consistent helix of the same length of wire it gave a very bright spark.

1097. Similar proofs can be drawn from the mutual inductive action of two separate currents (1110); and it is important

for the general principles that the consistent action of two such currents should be established. Thus, two currents, going in the same direction, should if simultaneously stopped, aid each other by their relative influence; or if proceeding in contrary directions should oppose each other under similar circumstances. I endeavored at first to obtain two currents from two different electromotors, and passing them through the helices *i* and *ii*, tried to effect the disjunctions mechanically at the same moment. But in this I could not succeed; one was always separated before the other, and in that case produced little or no spark, its inductive power being employed in throwing a current round the remaining complete circuit (1090): the current which was stopped last always gave a bright spark. If it were ever to become needful to ascertain whether two junctions were accurately broken at the same moment, these sparks would afford a test for the purpose, having an infinitesimal degree of perfection.

1098. I was able to prove the points by other expedients. Two short thick wires were selected to serve as terminations, by which contact could be made or broken with the electromotor. The compound helix consisting of *i* and *ii* (1053), was adjusted so that the extremities of the two helices could be placed in communication with the two terminal wires, in such a manner that the current moving through the thick wires should be divided into two equal portions in the two helices, these portions travelling, according to the mode of connexion, either in the same direction or in contrary directions at pleasure. In this manner two streams could be obtained, both of which could be stopped simultaneously, because the disjunction could be broken at G or F by removing a single wire. When the helices were in contrary directions, there was scarcely a sensible spark at the place of disjunction; but when they were in accordance there was a very bright one.

1099. The helix *i* was now used constantly, being sometimes associated, as above, with helix *ii* in an according direction, and sometimes with helix *iii*, which was placed at a little distance. The association *i* and *ii*, which presented two currents able to affect each other by induction, because of their vicinity, gave a brighter spark than the association *i* and *iii*, where the two streams could not exert their mutual influence; but the difference was not so great as I expected.

1100. Thus all the phenomena tend to prove that the effects are due to an inductive action, occurring at the moment when the principal current is stopped. I at one time thought they were due to an action continued during the *whole time* of the current, and expected that a steel magnet would have an influence according to its position in the helix, comparable to that of a soft iron bar, in assisting the effect. This, however, is not the case; for hard steel, or a magnet in the helix, is not so effectual as soft iron; nor does it make any difference how the magnet is placed in the helix, and for very simple reasons, namely, that the effect does not depend upon a permanent state of the core, but a *change of state;* and that the magnet or hard steel cannot sink through such a difference of state as soft iron, at the moment contact ceases, and therefore cannot produce an equal effect in generating a current of electricity by induction (34, 37).

1101. As an electric current acts by induction with equal energy at the moment of its commencement as at the moment of its cessation (10, 26), but in a contrary direction, the reference of the effects under examination to an inductive action, would lead to the conclusion that corresponding effects of an opposite nature must occur in a long wire, a helix, or an electro-magnet, every time that *contact is made* with the electromotor. These effects will tend to establish a resistance for the first moment in the long conductor, producing a result equivalent to the reverse of a shock or a spark. Now it is very difficult to devise means fit for the recognition of such negative results; but as it is probable that some positive effect is produced at the time, if we knew what to expect, I think the few facts bearing upon this subject with which I am acquainted are worth recording.

1102. The electro-magnet was arranged with an electrolyzing apparatus at *x,* as before described (1084), except that the intensity of the chemical action at the electromotor was increased until the electric current was just able to produce the feeblest signs of decomposition whilst contact was continued at G and E (1079) (the iodine of course appearing against the end of the cross-wire P); the wire N was also separated from A at *r,* so that contact there could be made or broken at pleasure. Under

these circumstances the following set of actions was repeated several times: contact was broken at *r*, then broken at G, next made at *r*, and lastly renewed at G; thus any current from N to P due to *breaking* of contact was avoided, but any additional force to the current from P to N due to *making* contact could be observed. In this way it was found, that a much greater decomposing effect (causing the evolution of iodine against P) could be obtained by a few completions of contact than by the current which could pass in a much longer time if the contact was *continued.* This I attribute to the act of induction in the wire ABD at the moment of contact rendering that wire a worse conductor, or rather retarding the passage of the electricity through it for the instant, and so throwing a greater quantity of the electricity, which the electromotor could produce, through the cross-wire passage NP. The instant the induction ceased, ABD resumed its full power of carrying a constant current of electricity, and could have it highly increased, as we know by the former experiments (1060) by the opposite inductive action brought into activity at the moment contact at Z or C was *broken.*

1103. A galvanometer was then introduced at *x*, and the deflection of the needle noted whilst contact was continued at G and E; the needle was then blocked as before in one direction (1087), so that it should not return when the current ceased, but remain in the position in which the current could retain it. Contact at G or E was broken, producing of course no visible effect; it was then renewed and the needle was instantly deflected, passing from the blocking pins to a position still further from its natural place than that which the constant current could give, and thus showing, by the temporary excess of current in this cross communication, the temporary retardation in the circuit ABD.

1104. On adjusting a platina wire at *x* (1081) so that it should not be ignited by the current passing through it whilst contact at G and E was *continued,* and yet become red hot by a current somewhat more powerful, I was readily able to produce its ignition upon *making contact,* and again upon *breaking contact.* Thus the momentary retardation in ABD on making contact was again shown by this result, as well also as the opposite result upon breaking contact. The two ignitions of the

wire at x were of course produced by electric currents moving in opposite directions.

1105. Using the *helix* only, I could not obtain distinct deflections at x, due to the extra effect on making contact, for the reasons already mentioned (1088). By using a very fine platina wire there (1083) I did succeed in obtaining the igniting effect for making contact in the same manner, though by no means to the same degree, as with the electro-magnet (1104).

1106. We may also consider and estimate the effect on *making contact,* by transferring the force of induction from the wire carrying the original current to a lateral wire, as in the cases described (1090); and we then are sure, both by the chemical and galvanometrical results (1091), that the forces upon making and breaking contact, like action and reaction, are equal in their strength but contrary in their direction. If, therefore, the effect on making contact, resolves itself into a mere retardation of the current at the first moment of its existence, it must be, in its degree, equivalent to the high exaltation of that same current at the moment contact is broken.

1107. Thus the case under the circumstances, is, that the intensity and quantity of electricity moving in a current are smaller when the current commences or is increased, and greater when it diminishes or ceases, than they would be if the inductive action occurring at these moments did not take place; or than they are in the original current wire if the inductive action be transferred from that wire to a collateral one (1090).

1108. From the facility of transference to neighboring wires, and from the effects generally, the inductive forces appear to be lateral, *i. e.,* exerted in a direction perpendicular to the direction of the originating and produced currents; and they also appear to be accurately represented by the magnetic curves, and closely related to, if not identical with, magnetic forces.

1109. There can be no doubt that the current in one part of a wire can act by induction upon other parts of the *same* wire which are lateral to the first, *i. e.,* in the same vertical section (74), or in parts which are more or less oblique to it (1112), just as it can act in producing a current in a neighboring wire or in a neighboring coil of the same wire. It is this which gives the appearance of the current acting upon itself; but all the experiments and all analogy tend to show that the elements (if I

may so say) of the currents do not act upon themselves, and so cause the effect in question, but produce it by exciting currents in conducting matter which is lateral to them.

1110. It is possible that some of the expressions I have used may seem to imply, that the inductive action is essentially the action of one current upon another, or of one element of a current upon another element of the same current. To avoid any such conclusion I must explain more distinctly my meaning. If an endless wire be taken, we have the means of generating a current in it which shall run round the circuit without adding any electricity to what was previously in the wire. As far as we can judge, the electricity which appears as a current is the same as that which before was quiescent in the wire; and though we cannot as yet point out the essential condition of difference of the electricity at such times, we can easily recognize the two states. Now when a current acts by induction upon conducting matter lateral to it, it probably acts upon the electricity in that conducting matter whether it be in the form of a *current* or *quiescent,* in the one case increasing or diminishing the current according to its direction, in the other producing a current, and the *amount* of the inductive action is probably the same in both cases. Hence, to say that the action of induction depended upon the mutual relation of two or more currents, would, according to the restricted sense in which the term current is understood at present (283, 517, 667), be an error.

1111. Several of the effects, as, for instance, those with helices (1066), with according or counter currents (1097, 1098), and those on the production of lateral currents (1090), appear to indicate that a current could produce an effect of induction in a neighboring wire more readily than in its own carrying wire, in which case it might be expected that some variation of result would be produced if a bundle of wires were used as a conductor instead of a single wire. In consequence the following experiments were made. A copper wire one twenty-third of an inch in diameter was cut into lengths of five feet each, and six of these being laid side by side in one bundle, had their opposite extremities soldered to two terminal pieces of copper. This arrangement could be used as a discharging wire, but the general current could be divided into six parallel streams, which might be brought close together, or, by the separation of the wires, be

taken more or less out of each other's influence. A somewhat brighter spark was, I think, obtained on breaking contact when the six wires were close together than when held asunder.

1112. Another bundle containing twenty of these wires, was eighteen feet long; the terminal pieces were one-fifth of an inch in diameter, and each six inches long. This was compared with nineteen feet in length of copper wire one-fifth of an inch in diameter. The bundle gave a smaller spark on breaking contact than the latter, even when its strands were held together by string; when they were separated it gave a still smaller spark. Upon the whole, however, the diminution of effect was not such as I expected; and I doubt whether the results can be considered as any proof of the truth of the supposition which gave rise to them.

1113. The inductive force by which two elements of one current (1109, 1110) act upon each other, appears to diminish as the line joining them becomes oblique to the direction of the current, and to vanish entirely when it is parallel. I am led by some results to suspect that it then even passes into the repulsive force noticed by M. Ampère;* which is the cause of the elevations in mercury described by Sir Humphrey Davy,† and which again is probably directly connected with the quality of intensity.

1114. Notwithstanding that the effects appear only at the making and breaking of contact (the current remaining unaffected, seemingly, in the interval), I cannot resist the impression that there is some connected and correspondent effect produced by this lateral action of the elements of the electric stream during the time of its continuance (60, 242). An action of this kind, in fact, is evident in the magnetic relations of the parts of the current. But admitting (as we may do for the moment) the magnetic forces to constitute the power which produces such striking and different results at the commencement and termination of a current, still there appears to be a link in the chain of effects, a wheel in the physical mechanism of the action, as yet unrecognized. If we endeavor to consider electricity and magnetism as the results of two forces of a

* *Recueil d'Observations Electro-Dynamiques*, p. 285.

† *Philosophical Transactions*, 1823, p. 155.

physical agent, or a peculiar condition of matter, exerted in determinate directions perpendicular to each other, then it appears to me that we must consider these two states or forces as convertible into each other in a greater or smaller degree; *i. e.,* that an element of an electric current has not a determinate electric force and a determinate magnetic force constantly existing in the same ratio, but that the two forces are, to a certain degree, convertible by a process or change of condition at present unknown to us. How else can a current of a given intensity and quantity be able, by its direct action, to sustain a state which, when allowed to react (at the cessation of the original current), shall produce a second current, having an intensity and quantity far greater than the generating one? This cannot result from a direct reaction of the electric force; and if it result from a change of electrical into magnetic force, and a reconversion back again, it will show that they differ in something more than mere direction, as regards *that agent* in the conducting wire which constitutes their immediate cause.

1115. With reference to the appearance at different times, of the contrary effects produced by the making and breaking contact, and their separation by an intermediate and indifferent state, this separation is probably more apparent than real. If the conduction of electricity be effected by vibrations (283), or by any other mode in which opposite forces are successively and rapidly excited and neutralized, then we might expect a peculiar and contrary development of force at the commencement and termination of the periods during which the conducting action should last (somewhat in analogy with the colours produced at the outside of an imperfectly developed solar spectrum): and the intermediate actions, although not sensible in the same way, may be very important and, for instance, perhaps constitute the very essence of conductibility. It is by views and reasons such as these, which seem to me connected with the fundamental laws and facts of electrical science, that I have been induced to enter, more minutely than I otherwise should have done, into the experimental examination of the phenomena described in this paper.

1116. Before concluding, I may briefly remark, that on using a voltaic battery of fifty pairs of plates instead of a single pair (1052), the effects were exactly of the same kind. The

spark, on making contact, for the reasons before given, was very small (1101, 1107); that on breaking contact, very excellent and brilliant. The *continuous* discharge did not seem altered in character, whether a short wire or the powerful electromagnet were used as a connecting discharger.

1117. The effects produced at the commencement and end of a current (which are separated by an interval of time when that current is supplied from a voltaic apparatus) must occur at the same moment when a common electric discharge is passed through a long wire. Whether, if happening accurately at the same moment, they would entirely neutralize each other, or whether they would not still give some definite peculiarity to the discharge, is a matter remaining to be examined; but it is very probable that the peculiar character and pungency of sparks drawn from a long wire depend in part upon the increased intensity given at the termination of the discharge by the inductive action then occurring.

1118. In the wire of the helix of magneto-electric machines (as, for instance, in Mr. Saxton's beautiful arrangement), an important influence of these principles of action is evidently shown. From the construction of the apparatus the current is permitted to move in a complete metallic circuit of great length during the first instants of its formation: it gradually rises in strength, and is then suddenly stopped by the breaking of the metallic circuit; and thus great intensity is given *by induction* to the electricity, which at that moment passes (1064, 1060). This intensity is not only shown by the brilliancy of the spark and the strength of the shock, but also by the necessity which has been experienced of well insulating the convolutions of the helix, in which the current is formed; and it gives to the current a force at these moments very far above that which the apparatus could produce if the principle which forms the subject of this paper were not called into play.

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EXPERIMENTAL RESEARCHES IN ELECTRICITY

By MICHAEL FARADAY

FOURTEENTH SERIES

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FOURTEENTH SERIES

§ 21. Relation of the Electric and Magnetic Forces

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1709. I have already ventured a few speculations respecting the propable relation of magnetism, as the transverse force of the current, to the divergent or transverse force of the lines of inductive action belonging to static electricity (1658, etc.).

1710. In the further consideration of this subject, it appeared to me to be of the utmost importance to ascertain, if possible, whether this lateral action which we call magnetism, or sometimes the induction of electrical currents (26, 1048, etc.), is extended to a distance *by the action of the intermediate particles* in analogy with the induction of static electricity, or the various effects, such as conduction, discharge, etc., which are dependent on that induction; or, whether its influence at a distance is altogether independent of such intermediate particles (1662).

1711. I arranged two magneto-electric helices with iron cores end to end, but with an interval of an inch and three quarters between them, in which interval was placed the end or pole of a bar magnet. It is evident, that on moving the magnetic pole from one core towards the other, a current would tend to form in both helices, in the one because of the lowering, and in the other because of the strengthening of the magnetism induced in the respective soft iron cores. The helices were connected together and also with a galvanometer, so that these two currents should coincide in direction, and tend by their joint force to deflect the needle of the instrument. The whole arrangement was so effective and delicate, that moving the magnetic pole about the eighth of an inch to and fro two or three times, in periods equal to those required for the vibrations of the galvanometer needle, was sufficient to cause considerable vibration in the latter; thus showing readily the consequence of

strengthening the influence of the magnet on the one core and helix, and diminishing it on the other.

1712. Then without disturbing the distances of the magnet and cores, plates of substances were interposed. Thus calling the two cores A and B, a plate of shell-lac was introduced between the magnetic pole and A for the time occupied by the needle in swinging one way; then it was withdrawn for the time occupied in the return swing; introduced again for another equal portion of time; withdrawn for another portion, and so on eight or nine times; but not the least effect was observed on the needle. In other cases the plate was alternated, *i. e.*, it was introduced between the magnet and A for one period of time, withdrawn and introduced between the magnet and B for the second period, withdrawn and restored to its first place for the third period, and so on, but with no effect on the needle.

1713. In these experiments *shell-lac* in plates 0.9 of an inch in thickness, *sulphur* in a plate 0.9 of an inch in thickness, and *copper* in a plate 0.7 of an inch in thickness were used without any effect. And I conclude that bodies, contrasted by the extremes of conducting and insulating power, and opposed to each other as strongly as metals, air, and sulphur, show no difference with respect to magnetic forces when placed in their lines of action, at least under the circumstances described.

1714. With a plate of iron, or even a small piece of that metal, as the head of a nail, a very different effect was produced, for then the galvanometer immediately showed its sensibility, and the perfection of the general arrangement.

1715. I arranged matters so that a plate of *copper* 0.2 of an inch in thickness, and ten inches in diameter, should have the part near the edge interposed between the magnet and the core, in which situation it was first rotated rapidly, and then held quiescent alternately, for periods according with that required for the swinging of the needle; but not the least effect upon the galvanometer was produced.

1716. A plate of shell-lac 0.6 of an inch in thickness was applied in the same manner, but whether rotating or not it produced no effect.

1717. Occasionally the plane of rotation was directly across the magnetic curve: at other times it was made as oblique as

possible; the direction of the rotation being also changed in different experiments, but not the least effect was produced.

1718. I now removed the helices with their soft iron cores, and replaced them by two *flat helices* wound upon cardboard, each containing forty-two feet of silked copper wire, and having no associated iron. Otherwise the arrangement was as before, and exceedingly sensible; for a very slight motion of the magnet between the helices produced an abundant vibration of the galvanometer needle.

1719. The introduction of plates of shellac, sulphur, or copper into the intervals between the magnet and these helices (1713), produced not the least effect, whether the former were quiescent or in rapid revolution (1715). So here no evidence of the influence of the intermediate particles could be obtained (1710).

1720. The magnet was then removed and replaced by a flat helix, corresponding to the two former, the three being parallel to each other. The middle helix was so arranged that a voltaic current could be sent through it at pleasure. The former galvanometer was removed, and one with a double coil employed, one of the lateral helices being connected with one coil, and the other helix with the other coil, in such manner that when a voltaic current was sent through the middle helix its inductive action (26) on the lateral helices should cause currents in them, having contrary directions in the coils of the galvanometer. By a little adjustment of the distances these induced currents were rendered exactly equal, and the galvanometer needle remained stationary notwithstanding their frequent production in the instrument. I will call the middle coil C, and the external coils A and B.

1721. A plate of copper 0.7 of an inch thick and six inches square, was placed between coils C and B, their respective distances remaining unchanged; and then a voltaic current from twenty pairs of 4-inch plates was sent through the coil C, and intermitted, in periods fitted to produce an effect on the galvanometer (1712), if any difference had been produced in the effect of C on A and B. But notwithstanding the presence of air in one interval and copper in the other, the inductive effect was exactly alike on the two coils, and as if air had occupied both intervals. So that notwithstanding the facility with which

any induced currents might form in the thick copper plate, the coil outside of it was just as much affected by the central helix C as if no such conductor as the copper had been there (65).

1722. Then, for the copper plate was substituted one of sulphur 0.9 of an inch thick; still the results were exactly the same, *i. e.,* there was no action at the galvanometer.

1723. Thus it appears that when a voltaic current in one wire is exerting its inductive action to produce a contrary or a similar current in a neighboring wire, according as the primary current is commencing or ceasing, it makes not the least difference whether the intervening space is occupied by such insulating bodies as air, sulphur, and shell-lac, or such conducting bodies as copper, and the other non-magnetic metals.

1724. A correspondent effect was obtained with the like forces when resident in a magnet thus. A single flat helix (1718) was connected with a galvanometer, and a magnetic pole placed near to it; then by moving the magnet to and from the helix, or the helix to and from the magnet, currents were produced indicated by the galvanometer.

1725. The thick copper plate (1721) was afterwards interposed between the magnetic pole and the helix; nevertheless on moving these to and fro, effects, exactly the same in direction and amount, were obtained as if the copper had not been there. So also on introducing a plate of sulphur into the interval, not the least influence on the currents produced by motion of the magnet or coils could be obtained.

1726. These results, with many others which I have not thought it needful to describe, would lead to the conclusion that (judging by the *amount* of effect produced at a distance by forces transverse to the electric current, *i. e.,* magnetic forces), the intervening matter, and therefore the intervening particles have nothing to do with the phenomena; or in other words, that though the inductive force of static electricity is transmitted to a distance by the action of the intermediate particles (1164, 1666), the transverse inductive force of currents, which can also act at a distance, is not transmitted by the intermediate particles in a similar way.

1727. It is, however, very evident that such a conclusion cannot be considered as proved. Thus, when the metal copper is between the pole and the helix (1715, 1719, 1725) or between

the two helices (1721) we know that its particles are affected, and can by proper arrangements make their peculiar state for the time very evident by the production of either electrical or magnetical effects. It seems impossible to consider this effect on the particles of the intervening matter as independent of that produced by the inductric coil or magnet C, on the inducteous coil or core A (1715, 1721); for since the inducteous body is equally affected by the inductric body whether these intervening and affected particles of copper are present or not (1723, 1725), such a supposition would imply that the particles so affected had no reaction back on the original inductric forces. The more reasonable conclusion, as it appears to me, is, to consider these affected particles as efficient in continuing the action onwards from the inductric to the inducteous body, and by this very communication producing the effect of *no loss* of induced power at the latter.

1728. But then it may be asked what is the relation of the particles of insulating bodies, such as air, sulphur, or lac, when *they* intervene in the line of magnetic action? The answer to this is at present merely conjectural. I have long thought that there must be a particular condition of such bodies corresponding to the state which causes currents in metals and other conductors (26, 53, 191, 201, 213); and considering that the bodies are insulators one would expect that state to be one of tension. I have by rotating non-conducting bodies near magnetic poles and poles near them, and also by causing powerful electric currents to be suddenly formed and to cease around and about insulators in various directions, endeavored to make some such state sensible, but have not succeeded. Nevertheless, as any such state must be of exceedingly low intensity, because of the feeble intensity of the currents which are used to induce it, it may well be that the state may exist, and may be discoverable by some more expert experimentalist, though I have not been able to make it sensible.

1729. It appears to me possible, therefore, and even probable, that magnetic action may be communicated to a distance by the action of the intervening particles, in a manner having a relation to the way in which the inductive forces of static electricity are transferred to a distance (1677); the intervening particles assuming for the time more or less of a peculiar con-

dition, which (though with a very imperfect idea) I have several times expressed by the term *electro-tonic state* (60, 242, 1114, 1661). I hope it will not be understood that I hold the settled opinion that such is the case. I would rather in fact have proved the contrary, namely, that magnetic forces are quite independent of the matter intervening between the inductric and the inducteous bodies; but I cannot get over the difficulty presented by such substances as copper, silver, lead, gold, carbon, and even aqueous solutions (201, 213), which though they are known to assume a peculiar state whilst intervening between the bodies acting and acted upon (1727), no more interfere with the final result than those which have as yet had no peculiarity of condition discovered in them.

1730. A remark important to the whole of this investigation ought to be made here. Although I think the galvanometer used as I have described it (1711, 1720) is quite sufficient to prove that the final amount of action on each of the two coils or the two cores A and B (1713, 1719) is equal, yet there is an effect which *may* be consequent on the difference of action of two interposed bodies which it would not show. As time enters as an element into these actions* (125), it is very possible that the induced actions on the helices or cores, A, B, though they rise to the same degree when air and copper, or air and lac are contrasted as intervening substances, do not do so in the same time; and yet, because of the length of the time occupied by a vibration of the needle, this difference may not be visible, both effects rising to their maximum in periods so short as to make no sensible portion of that required for a vibration of the needle, and so exert no visible influence upon it.

1731. If the lateral or transverse force of electrical currents, or what appears to be the same thing, magnetic power, could be proved to be influential at a distance independently of the intervening contiguous particles, then, as it appears to me, a real distinction, of a high and important kind, would be established between the natures of these two forces (1654, 1664).

* See *Annales de Chémie*, 1833, tom. li, pp. 422, 428.

I do not mean that the powers are independent of each other and might be rendered separately active, on the contrary they are probably essentially associated (1654), but it by no means follows that they are of the same nature. In common statical induction, in conduction, and in electrolyzation, the forces at the opposite extremities of the particles which coincide with the lines of action, and have commonly been distinguished by the term electric, are polar, and in the cases of contiguous particles act only to insensible distances; whilst those which are transverse to the direction of these lines, and are called magnetic, are circumferential, act at a distance, and if not through the mediation of the intervening particles, have their relations to ordinary matter entirely unlike those of the electrical forces with which they are associated.

1732. To decide this question of the identity or distinction of the two kinds of power, and establish their true relation, would be exceedingly important. The question seems fully within the reach of experiment, and offers a high reward to him who will attempt its settlement.

1733. I have already expressed a hope of finding an effect or condition which shall be to statical electricity what magnetic force is to current electricity (1658). If I could have proved to my own satisfaction that magnetic forces extended their influence to a distance by the conjoined action of the intervening particles in a manner analogous to that of electrical forces, then I should have thought that the lateral tension of the lines of inductive action (1659), or that state so often hinted at as the electro-tonic state (1661, 1662), was this related condition of statical electricity.

1734. It may be said that the state of *no lateral action* is to static or inductive force the equivalent of *magnetism* to current force; but that can only be upon the view that electric and magnetic action are in their nature essentially different (1664). If they are the same power the whole difference in the results being the consequence of the difference of *direction,* then the normal or *undeveloped* state of electric force will correspond with the state of *no lateral action* of the magnetic state of the force; the electric current will correspond with the lateral effects commonly called magnetism: but the state of static induction which is between the normal condition and the current

will still require a corresponding lateral condition in the magnetic series, presenting its own peculiar phenomena; for it can hardly be supposed that the normal electric, and the inductive or polarized electric condition, can both have the same lateral relation. If magnetism be a separate and a higher relation of the powers developed, then perhaps the argument which presses for this third condition of that force would not be so strong.

1735. I cannot conclude these general remarks upon the relation of the electric and magnetic forces without expressing my surprise at the results obtained with the copper plate (1721, 1725). The experiments with the flat helices represent one of the simplest cases of the induction of electrical currents (1720); the effect, as is well known, consisting in the production of a momentary current in a wire at the instant when a current in the contrary direction begins to pass through a neighboring parallel wire, and the production of an equally brief current in the reverse direction when the determining current is stopped (26). Such being the case, it seems very extraordinary that this induced current which takes place in the helix A when there is only air between A and C (1720) should be equally strong when that air is replaced by an enormous mass of that excellently conducting metal copper (1721). It might have been supposed that this mass would have allowed of the formation and discharge of almost any quantity of currents in it, which the helix C was competent to induce, and so in some degree have diminished if not altogether prevented the effect in A: instead of which, though we can hardly doubt that an infinity of currents are formed at the moment in the copper plate, still not the smallest diminution or alteration of the effect in A appears (65). Almost the only way of reconciling this effect with generally received notions is, as it appears to me, to admit that magnetic action is communicated by the action of the intervening articles (1729, 1733).

1736. This condition of things, which is very remarkable, accords perfectly with the effects observed in solid helices where wires are coiled over wires to the amount of five or six or more layers in succession, no diminution of effect on the outer ones being occasioned by those within.

BIOGRAPHICAL SKETCH.

MICHAEL FARADAY was born in Newington, Surrey, England, September 22, 1791, and died in London, August 25, 1867. He was apprenticed when thirteen years of age to a bookbinder; but, becoming interested in Davy's lectures on chemistry before the Royal Institution, he applied in 1813 to Davy for some position in his laboratory. His request was granted; and at first his duties were those of an under-assistant. He soon, however, attained distinction, became Director of the Laboratory of the Royal Institution, and in 1833 was appointed Fullerian Professor of Chemistry at this Institution, a position which he held until his death.

Previous to 1831, Faraday's work had been along lines of chemical investigations; but on August 29 of that year he began his famous "Researches in Electricity," which led him almost immediately to the independent discovery of induced currents, a year after they were discovered by Henry. In the course of these "Researches" Faraday formed the conception of "lines of force," one of the greatest aids to scientific thought and expression. He explained Arago's disc, studied the earth's magnetic field, made the first dynamo, and rediscovered currents of self-induction. He proved further the identity of electricities obtained in all possible ways. In 1833 he began his famous electro-chemical researches which led him to the discovery of the laws of electrolysis. He investigated also the origin of the electro-motive force in a Voltaic cell, rediscovered in 1837 the property of a dielectric called its Specific Inductive Capacity (first noted by Cavendish in 1772), discovered in 1845 the rotation of the plane of polarization of light by the magnetic field, and in the same year made his investigation on the "Magnetic Condition of All Matter," in the course of which he rediscovered "diamagnetism," a property previously observed in isolated cases by Becquerel and others.

A good summary of Faraday's characteristics as a scientist is given by his biographer Dr. Bence Jones:

"As a philosopher, his first great characteristic was the trust which he put in facts. He said of himself, 'In early life I was a very lively imaginative person, who could believe

in the "Arabian Nights" as easily as in the "Encyclopædia," but facts were important to me and saved me. I could trust a fact.' Over and over again he showed his love of experiments in his writings and lectures: 'Without experiment I am nothing.' 'But still try, for who knows what is possible?' 'All our theories are fixed upon uncertain data, and all of them want alteration and support from facts.' 'One thing, however, is fortunate, which is, that whatever our opinions, they do not alter nor derange the laws of nature.'

"His second great characteristic was his imagination. It rose sometimes to divination, or scientific second sight, and led him to anticipate results that he or others afterwards proved to be true."

Faraday's "Experimental Researches in Electricity" have been published in three volumes by Bernard Quaritch, London.

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THE END

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